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Decarbonisation of the Energy System: Transition to a Secure and Low-Carbon Energy System in the Largest Economies of Europe

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ABSTRACT OF THESIS submitted by:
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for the degree of Master of Science and entitled: *Decarbonisation of the Energy System : Transition to a Secure and Low-Carbon Energy System in the Largest Economies of Europe*
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The global energy system is going through a transition phase due to advancing climate change and depletion of fossil fuel resources. For the successful transition, it is necessary to decarbonise the energy system by reducing CO2 emissions and ensuring a security of supply. Therefore, the aim of this thesis has been to build a secure and low-carbon energy system while identifying the optimal energy mix in the largest economies of Europe with an outlook to 2050. This study analyses and compares the approaches of Germany, France and the United Kingdom to achieve decarbonisation targets defined in their respective energy transition plans by 2030 and 2050. This research describes the methodology of using the analytical transition framework where historical decarbonisation trends during 1990-2015 have been analysed to determine the energy consumption patterns. Further, a modelling framework is used where scenarios are developed for secure and low carbon energy future. Both the historical and future trends have been analysed considering the five key elements of energy transition i.e. energy supply side, energy demand side, CO2 emissions reduction, security of supply, and renewables in electricity generation. The obtained results show that all the three countries shift from fossil fuel to low carbon energy supply sources, reduces their energy demand, reduces the CO2 emissions, reduces the fossil fuel import, and increases the share of renewables in electricity generation. Further, the study suggests that the decarbonisation of the energy system is possible with expansion of renewable energy sources, deployment of low carbon technologies, electrification of end-use sectors, and increase in energy efficiency. The thesis concludes that all the three European countries have successfully achieved their decarbonisation targets and transition to a low carbon economy by 2050.

Keywords: Energy Transition, decarbonisation, climate change, security of supply, renewable energy sources, energy efficiency, electrification, low carbon economy

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List of Abbreviations

IPCC – Intergovernmental Panel on Climate Change

UNFCCC- United Nations Framework Convention on Climate Change

SDG – Sustainable Development Goals

IEA – International Energy Agency

OECD – Organisation for Economic Co-operation and Development

IRENA – International Renewable Energy Agency

RES - Renewable Energy Sources

FIT – Feed-in-tariffs

RO – Renewables Obligation

CfDs – Contracts for Difference

LNG – Contracts for Difference

bcm – billion cubic meters

TPES – Total Primary Energy Supply

TFC – Total Final Consumption

UK – United Kingdom

CHAPTER 1

INTRODUCTION

Today, the global energy system is facing an 'Energy Trilemma'[1] challenge. In the past two decades, the term 'Energy Transition' and 'Decarbonization' has gained great importance. World Energy Council define energy transition as "a fundamental structural change in the energy sector of a certain country, like the increasing share of renewable energies and the promotion of energy efficiency combined with phasing out fossil energies"[2]. An energy transition is also defined as "a shift in the nature or pattern of how energy is utilized within a system" (Araujo 2014:12). Also, the energy transition entails shifting from fossil fuels to low-carbon energy sources in the primary energy consumption and improvement in energy efficiency to reduce the final energy consumption (World Watch Institute 2013). Furthermore, decarbonisation is defined as "a continuous lowering of the carbon emissions per unit energy used, improving energy efficiency and curbing energy demand" (Hiteva 2017, p.121). Grubler defined as "a decrease in the specific amount of carbon (or CO2) emitted per unit of primary energy consumed. Structural changes in energy supply lead to decarbonization because the emission factors of different fuels vary". According to Barker & Crawford-Brown, decarbonisation is a continuous process to achieve low carbon economy through the reduction of CO2 emissions. To summarize, energy transition or decarbonisation of the energy system is defined as decarbonizing the energy supply and reducing the energy demand through the energy efficiency improvement.

Energy development is essential for any country's growth, but at the same time energy transition must address climate change challenge that stemmed from the energy sources. Decarbonisation of the energy system in the energy transition

[1] Energy Trilemma definition - Available at https://www.worldenergy.org/wp-content/uploads/2016/05/World-Energy-Trilemma_full-report_2016_web.pdf

[2] Energy Transition definition – Available at https://www.atkearney.com/documents/10192/5293225/Global+Energy+Transitions.pdf/220e6818-3a0a-4baa-af32-8bfbb64f4a6b

process is a need of the moment as it is widely accepted that energy-related CO2 emission is a key driver for climate change (IPCC, 2007). Moreover, key energy drivers for a sustainable development are energy security and climate change mitigation (IEA/OECD, 2008). Limiting the global average temperature below 2 °C and meeting energy demand in a secure and sustainable manner are two big challenges that need to be addressed simultaneously. Globally, due to economic and population growth, final energy consumption has increased. In the meantime, the issue of energy security also came into the limelight because of depleting fossil energy resources and high dependence on import of fossil fuel resources. Therefore, the concerns of depleting fossil fuels and climate change triggered the need of sustainable transition in the country's energy system. Thus, my thesis focuses on the two pillars of 'energy trilemma' and identifies the strategies for energy security and environmental sustainability i.e. decarbonisation with an aim to have low emission, clean and secure energy system.

International agreements and national energy transition plans play an important role towards a low-carbon energy system. 2015 was considered as a landmark year in terms of global effort to act on the climate change. In November 2015, Paris witnessed the global efforts to limit global carbon emissions and committed to hold the increase in temperature in range of 2°C. Earlier, in the same year during the Group of Seven (G7) meeting, G7 countries (the United States, Canada, Japan, Italy, France, Germany and the UK) committed for decarbonization of the global economy by 2100. Additionally, G7 leaders decided to reduce 40 to 70 % of global emission and energy sectors transformation of G7 countries by 2050 (G7 Germany, 2015)

Under the commitment of Paris Agreement and country's energy transition plan, this thesis focuses on European G7 countries or Europe's three largest economies, including Germany, France and the United Kingdom (UK). These European countries have traditionally made efforts to address climate change and represent a relatively less percentage of global emissions, and also continue to push for low carbon technologies in their energy system. Furthermore, Germany, France and the UK can set an example and provide solutions to other countries around the world, in

particular the European Union (EU) countries to decarbonise their economies and fight against climate change.

The research begins with a review of energy transition plans and legislations of Germany, France and the UK. Further, the study examines the historical analysis of decarbonisation in these European countries. It analyses decarbonization trends of primary energy consumption, final energy consumption, security of supply, CO2 emissions reduction and renewables in electricity generation. The research also analyses the mid-term and long-term decarbonisation of the energy system and demonstrates how these countries transition into low-carbon economies under the Paris Agreement and national decarbonisation targets. It investigates the patterns of energy mix changes from 2015 to 2050. The research concludes with a discussion of the challenges and opportunities with policy recommendations to facilitate the transition to a low carbon economy.

1.1 Background and Context

Climate change is the biggest challenge facing humanity in the 21st century (IPCC, 2014a). It jeopardizes the economic growth, human well-being, ecological safety, and available resources. Human activity, particularly burning fossil fuels is the main cause of current climate change due to emission of greenhouse gases. These GHGs accumulate in the earth's atmosphere, which leads to the less heat escape into space and thereby an increase in temperature (IPCC).

Since the 19th century the problem of global warming has been aggravated due to the increase in GHG emissions levels, particularly CO2 emissions. Since industrial revolution the atmospheric concentration of CO2 has increased from 280 parts per million (ppm) to 410 ppm in January, 2019[3]. Astonishingly, the rise of emission has increased rapidly since the 1950s. As a result, the increased level of emissions led to increase in global temperature. The global mean surface temperature increased by 0.74 ±0.18°C in the 20th century and is likely to increase by between 1.4 and 5.8°C by the end of 21st century from 1990 (IPCC, 2001b). However, the IPCC (2007) has

[3] Global carbon dioxide growth in 2018 reached 4th highest on record. Available at https://www.noaa.gov/news/global-carbon-dioxide-growth-in-2018-reached-4th-highest-on-record

set a CO2 concentration target of 450 ppm to limit the global average temperature rise to 2^{O}C. They also demonstrated that the rise of global average temperature can be limited between 2 and 2.4^{o}C (350-400 ppm CO2) only through 50% to 85% CO2 emissions reduction by 2050 relative to 2000 level. Following table: 1 shows the relationship between GHG concentration and climate change.

Table 1: 'The relationship between GHG concentration and climate change' (Source: IPCC, 2017)

Temperature increase (^{O}C)	GHGs (ppm CO_2 equivalent)	CO_2 (ppm)	Reduction of CO_2 emissions by 2050 (% of 2000 emissions)
2.0-2.4	445-490	350-400	50 to 85
2.4-2.8	490-535	400-440	30 to 60
2.8-3.2	535-590	440-485	5 to 30

At a global level, world leaders have responded to the climate change challenge through several international agreements. For example, the United Nations Framework Convention on Climate Change (UNFCCC) established in 1992 with an objective to achieve the "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system (…) within a time frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner" (Article 2 of (UNFCCC, 1992)). After the five years of the UNFCCC establishment, Kyoto Protocol was created in 1997 with an aim to reduce the GHG emissions (UN, 1998). The first commitment period started from 2008-2012 in which industrialized countries (known as 'Annex 1' nations)[4] committed targets to reduce GHG emissions by 5% below 1990 levels. The new target to reduce GHG emissions by 18% below 1990 levels was committed under the second commitment period (2013-2020). Later in the 21st century, global efforts have been accelerated to reduce GHG emissions and to limit global average temperature. First, the 2010 Cancun Agreement (UN, 2010), in which countries have agreed to limit global temperature by 2 °C compared to pre-

[4] **Annex** I Parties include the industrialized **countries** that were members of the OECD (Organisation for Economic Co-operation and Development) in 1992, plus **countries** with economies in transition (the EIT Parties), including the Russian Federation, the Baltic States, and several Central and Eastern European States , Available at http://www.oecd.org/env/cc/listofannexicountries.htm

industrial levels through limiting the CO2 concentration in the range of 450ppm-490ppm, of which requires a reduction in global emissions in the range of 50-85% by 2050 compared to 2000 levels . Second, the G7 Summit, in 2015, in which the G7 leaders committed to decarbonise the global economy by the end of century; reduce 40 to 70% of global emission and energy sectors transformation of G7 nations by 2050 (G7 Summit, 2015). Third, Sustainable Development Goals (SDGs) (UN, 2015), in which 2030 agenda was created for 17 SDGs including SDG 7 and SDG 13 for sustainable energy and climate change respectively; and fourth, the Paris Agreement (UNFCCC, 2015) in 2015, to strengthen the 2010 Cancun Agreement commitment to well below 2°C. It was the new agreement in which about 200 nations committed in the form of "Intended Nationally Determined Contributions[5]" (INDCs) targets to reduce their GHG emissions in 2030. At the end of July 2018, 179 countries ratified the Paris Agreement; as a result, INDCs change into "Nationally Determined Contributions" (NDCs)[6] . In October, 2018, IPCC published the "special report on global warming of 1.5 °C" in which it shows the urgency to limit global warming to 1.5 °C through reducing emissions to zero by 2050.

Energy sector is one of the key sectors for basic human needs and country's economic growth. Energy-related activities are the biggest contributor to GHG emissions due to exploitation of fossil fuels, which in turn, has made the energy sector a leading sector in efforts to mitigate climate change (IEA, 2009). During the past three decades, about 70 percent of global CO2 emissions have come from combustion of fossil fuels, with coal being a major source (IPCC 2007). In addition, globally, about 80% of the primary energy comes from fossil fuels burning (IEA, 2009). The final energy consumption has increased enormously in last fifty years and most of it comes from fossil fuels burning. The burning of fossil fuels also causes other environmental problems including atmospheric pollution and acidification (UNDP, 1997). The fossil fuel combustion process produces a large amount of dangerous pollutants in the form of nitrogen oxides (NOx), sulphur dioxides (SO2),

[5] Adopted by the Conference of the Parties of the UN Framework Convention on Climate Change at its nineteenth session". United Nations. 31 January 2014. Retrieved 15 December 2015. Available at https://www4.unfccc.int/sites/submissions/INDC/Submission%20Pages/submissions.aspx

[6] Paris Climate Agreement. Available at https://www.nrdc.org/stories/paris-climate-agreement-everything-you-need-know

hydrocarbons (HC), carbon monoxide (CO) and particulate matter (PM), which are responsible for air pollution. Therefore, a large amount of fossil fuel reduction is needed in order to mitigate the emissions and can be achieved by decarbonizing the energy system.

Limiting global average temperature and improving energy security requires large action to the current energy system in the form of energy transition and decarbonisation. Decarbonisation of energy system is vital to curb GHG emissions. To achieve this, both energy supply and demand decarbonisations are crucial for a energy system transformation because the emissions must be tackled from supply side i.e. where the energy supply comes from and demand side i.e. how much it consumes. Energy efficiency and renewable energy are two pillars of energy transition, where energy efficiency helps in reducing energy demand, which in turn, reduces emissions, while renewable energy helps in improving the security of supply through reducing the dependence on imported fossil fuels.

1.2 Statement of purpose

Energy security and environmental sustainability are two key elements of Energy Trilemma. The progress of the country's energy transition is determined by the performance of these two elements in the energy system. Germany, France and the UK are leading countries contributing to global energy transition and climate change policies. These countries have been pioneers in transforming their national policies into energy transition plans. All these countries have improved their security of supply and significantly reduced the carbon emissions due to set out mid-term and long-term ambitious targets. These countries have taken a lead in the development and investment in clean technologies. The world, especially Europeans, see these countries for leadership on climate and energy policies.

The three countries started their environmental and energy security concerns after the oil crisis in the 1970s, where Germany and the UK invested in coal while France opted for nuclear power to secure their energy supply. The climate change concerns were recognized by these countries in the 1990s. All these countries peaked their emissions in the 1990s. From the 2000s, these countries strengthened their climate

polices and established an energy transition plan in the form of laws and Act. It was also the official start date of their energy transition process. Decarbonisation of the energy system was the main aim of their energy transition plans, in which decarbonisation targets were defined until the middle of the 21st century. The UK was the first country to set a long-term decarbonisation targets in 2008 for 2050, while Germany and the France set the targets in 2010 and 2015, respectively for 2050. Germany, France and the UK committed to medium term and long term targets through the establishment of Energiewende, Energy Transition Law, and the Climate Change Act, respectively.

Presently, the energy sector of these countries are in a transition phase due to several important decisions have taken by their respective governments. Germany and the UK aimed to reduce their coal reliance and committed to phase-out the coal plants by 2038 and 2025, respectively while France aimed to reduce their nuclear share from 75% to 50% in its electricity mix. In addition, a significant number of nuclear plants and coal-fired plants are at the end of their life span. To tackle climate change, these countries government can invest in the expansion of clean technologies, especially renewable energy sources. Therefore, in view of changes in the future energy sector of these countries, the thesis is focused on analysis of energy system in the context of climate change and energy security. The study also provides comparisons and analysis of historical and planned approaches to transition to a secure and low-carbon energy system by 2030 and 2050 in these three countries.

1.3 Aim and scope

According to the IPCC 2007 report, it is essential to reduce the GHG emissions in the range of 50% to 85% in order to limit the global average temperature below 2^{o}C and prevent the anthropogenic climate change. Therefore, Germany, France and the UK have set decarbonisation targets of reduction in 80-95%, 75% and 80% GHG emissions, respectively by 2050 relative to 1990 levels in their energy transition plans.

Based on the above considerations, the aim of this thesis is to build a secure and climate-friendly energy system in the three largest economies of Europe by mid-century.

In doing so, the thesis assesses historical emission trends and project future trends in order to achieve these decarbonisation targets in Germany, France and the UK. The scope of this study is to gain insight into how the energy system of these countries can be decarbonized by 2050 while maintaining the security of supply by using a historical analytical transition framework and modeling-scenario framework.

1.4 Objectives and research questions

To pursue the above aim, the thesis addresses the following objectives:

- To analyse the historical energy transitions of these countries and identify drivers for the changes in the energy mix, energy demand, and CO2 emissions during 1990-2015.
- To develop an energy model and analyse the future scenario with an outlook to 2030 and 2050 considering energy security and environmental sustainability.
- To explore low-carbon energy solutions to move towards secure and climate friendly energy system.
- To determine the optimal energy mix for low-carbon energy system in 2030 and 2050.

To achieve research objectives, the study investigates the following research questions.

- What are the most appropriate low carbon sources in the primary energy supply for decarbonisation?
- What are the end-use sectors that can most effectively contribute to meet decarbonisation targets?
- What will be the share of renewables in the electricity mix?
- How can import dependence on fossil fuels be reduced?
- Are these countries having similar approaches to decarbonisation?

1.5 Focus of work

The focus of the study will be on analysis of selected key elements of energy transition:

Energy supply side

The study analysis the total primary energy supply (TPES) by sources for three countries. The decarbonization of energy supply will be assessed and prospects for low carbon energy supply options will also be identified. Further, the impact of low carbon energy supply on CO2 emissions will be examined.

Energy demand side

This part explores the role of energy efficiency and renewable in the final energy consumption. The reduction of final energy consumption through energy efficiency and the increase of share of renewables in the end-use sectors will be examined. It also explores the strategies for reduction in energy demand in building and transport sectors.

Climate change mitigation – CO2 emissions reduction

This part assesses the mitigation of climate change through the reduction of energy-related CO2 emissions in the atmosphere. It explores the historic decarbonisation trends and investigates the measures to achieve CO2 emission reduction targets by 2030 and 2050. It also examines the sources of CO2 emissions as well as CO2 emissions by secor.

Energy security – Security of supply

This part assesses the country's energy security situation through the indicator of net energy imports. It also entails the country's approach to reduce the reliance on imported energy and explore the fossil fuels options.

Renewables in electricity generation

This part examines the share of sources in the electricity generation and electricity generation from renewables by source. It discusses that the increasing share of renewables in the electricity mix plays an important role in reducing CO2 emissions and thereby achieve decarbonisation targets. .

1.6 Structure of the thesis

The thesis is structured as follows:

Chapter 1 provides the introductory chapter, in which the overview, background and context, statement of the purpose, aim and scope, objectives and research questions, and thematic focus areas are presented.

Chapter 2 contains the literature review which provides a description and development of current energy transition plans i.e. Energy Concept, Energy Transition Law and the Climate Change Act for Germany, France and the UK, respectively.

Chapter 3 provides the analytical transition framework in which historical decarbonisation trends of these countries have analyzed. This chapter also provides the comparative analysis of historical decarbonisation in Germany, France and the UK.

Chapter 4 provides the modeling framework in which energy model is developed and scenarios are designed to achieve mid-term and long-term decarbonisation targets. The model determined the optimal energy mix and explores how the current energy system will change to a low carbon energy system in 2030 and 2050. This chapter also provides the comparison and analysis of short term and long term scenarios between Germany, France and the UK.

Chapter 5 provides a summary, conclusions and recommendations.

CHAPTER 2

LITERATURE REVIEW

In the chapter, literature review has been conducted with the intention of determining assumptions and projections in the scenario development. This chapter reviews the energy transition plans of Germany, France and the United Kingdom (UK). These countries have established energy transition plans and have set long-term decarbonisation targets aimed at mitigating climate change. To understand how these countries can decarbonize their energy sector and move towards a secure and climate-friendly energy system, it is important to identify what is included in the energy transition plan, what are its targets, and what is the current situation. Therefore, this chapter tries to shed light on their current energy policies, targets and objectives, and the historical development of the energy transition plans.

2.1 Energy Transition in Germany

Germany's energy transition, 'Energiewende' has a worldwide significance and it has become an ambitious and pioneering initiative to develop a country's low-carbon energy system for ongoing global energy transition. The German energy transition is characterized by expansion of renewable energy sources (RES), improving energy efficiency and phase-out of nuclear power plants. The renewable energy sources have increased through a scheme of feed-in-tariff and Renewable Energy Sources Act (EEA), while the phase-out of nuclear power plants under the Energy Concept.

The German energy transition is driven by three objectives: climate change mitigation, security of supply, and phasing-out nuclear power plants. The goal of the German Energiewende is to reduce 80-95% carbon emissions by 2050, decarbonizing the energy supply through renewables by 2050 and phase-out nuclear power plants by 2022. These objectives can be achieved by two pillars of energy transition i.e. renewable energy and energy efficiency. Furthermore, Energiewende is based on two components of German energy policies, namely the Renewable Energy Sources Act (Erneuerbare Energien Gesetz, EEG), which promotes the

renewable energy sources in the energy and electricity mix; and the Energy Concept (Energiekonzept), which promotes the low carbon energy system.

2.1.1 Development of Germany's Energy Transition (Energiewende)

The Energiewende is a continuous process of the German energy system which has no official start date. It builds on several government laws and regulations of German energy policy since 1974 in a response to the oil crisis. In 1980, the term 'Energiewende' was first coined by Öko-Institut in its publication for a clean energy future without nuclear energy and fossil fuels (Krause & Müller 1980). However, in 2010, it was introduced officially in the policy document 'Energy Concept'.

The development of Energiewende can be summarized in five decades from 1970-present.

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1970s - This is the decade when the roots of the transition developed in the quest of different sources of energy. The 1970's oil crisis, rising anti-nuclear and ecological movements triggered the vision for alternative energy sources in view of concern for energy security, safety and environmental impact. However, in this decade, energy security was the main focus of German energy system.

1980s - In this decade, the main focus of energy policy was safety because of the Chernobyl nuclear disaster in 1986. After the accident in Chernobyl nuclear power plant in Ukraine, all planned nuclear plants were abandoned and no new reactors were constructed in this decade. In addition, the nuclear accident sent acid rain over Germany in which many forests were affected, which gave rise to environmental movement against nuclear power plants. Furthermore, a report on climate change and its consequences was published in 1986, which attracted the attention of climate protection for the first time in the political agenda. Therefore, environmental and climate protection also became a matter of concern at the end of the decade.

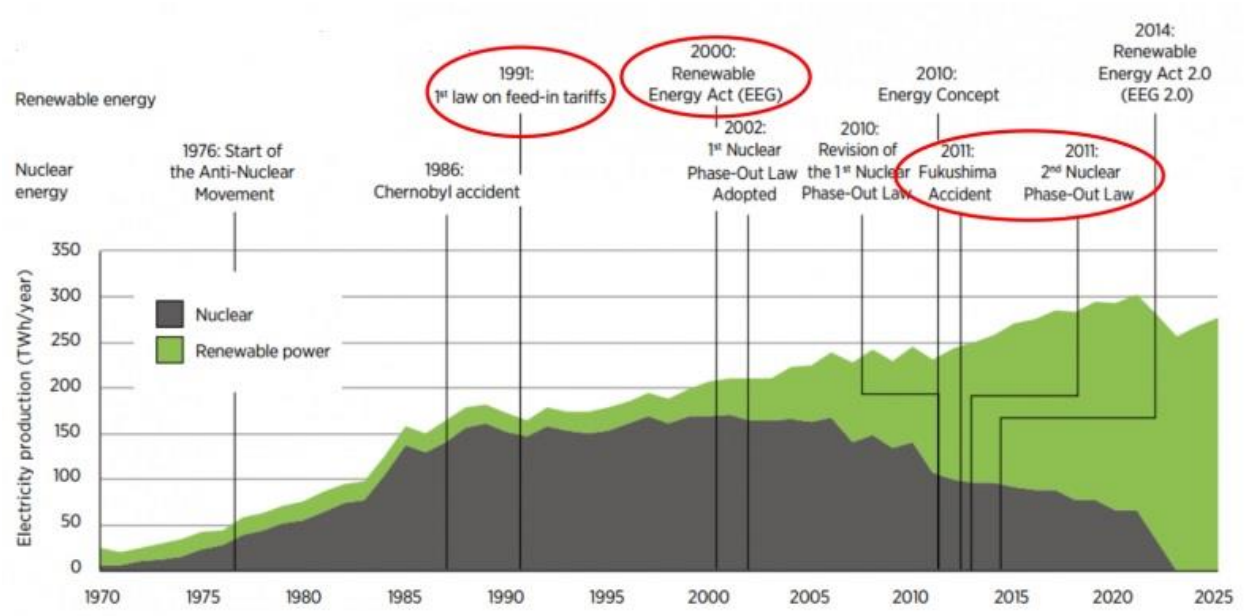


Fig.1 Energiewende important energy policies and historical events (Source: IRENA)

1990s - Climate change mitigation and nuclear phase-out were the main focus areas during this decade. Germany started to push renewable energy in its energy mix with the Feed-in-Act in 1991. However, progress was slow during this period. In 1991, Germany enacted the Grid feed-in-tariff law (Stromeinspeisungsgesetz – StromEinspG) for promoting renewable energy sources (RES). The push for RES was connected to the concern of climate change. Actually, the renewable energy sources were seen as an alternative to nuclear energy. In the end of the decade, in the 1998 elections, the Germans chose a coalition government run by Social Democrats and Greens from which the transition movement was further strengthened whose priority was “ecological modernization”.

2000s- From 2000 to 2009, the German government adopted three important energy policies. First, Renewable Energy Sources Act (Erneuerbare Energien Gesetz, EEG) was introduced in the year 2000. In fact, EEG was the replacement of the Stromeinspeisungsgesetz. The Act is a fixed feed-in tariff subsidy scheme which supports the expansion of renewable energy generation capacity. The three quantitative targets set out in this Act – 40 to 45% by 2025; 55 to 60% by 2035; and at least 80% by 2050. Second, in 2007, Integrated Energy and Climate Programme was adopted, consisting of three objectives of environmental protection, security of

supply and economic efficiency. The Programme contained 29 measures and the quantitative goals set out for climate protection, expansion of renewable energies and improving energy efficiency. The Programme aimed to reduce GHG emissions by 40% to 2020 relative to 1990 level. Third, first law on nuclear phase-out was introduced by the German government in 2002. This law stipulates the closure of all nuclear plants by 2022.

2010s – In the present decade, Energiewende became a mainstream through two major policy decisions taken by the German government. Firstly, in 2010, the government adopted the Energy Concept (Energiekonzept), which established the short term (2020), mid-term (2030) and long term (2050) emission reduction targets. It outlines to achieve “an environmentally sound, reliable and affordable energy supply”. The Energy Concept developed with more ambitious goals from the 2007 Integrated Energy and Climate Programme

Secondly, the Federal government decided to move to the low carbon energy system while adopting policy measures to accelerate the energy transition, which is known as the “Energiewende”. It was the first time when the term ‘Energiewende’ was officially introduced in the energy policy document. The key elements of the Energiewende were to expand renewable energy sources, improve energy efficiency, reform the fund, and reverse the 2001 decision of nuclear phase-out and extend the commission of nuclear plants by 2036. However, the decision was amended immediately after the Fukushima nuclear accident in 2011, where the government passed the law to phase-out of nuclear power by 2022.

In addition, in the present decade, the Renewable Energy Act (EEG) was revised three times in 2012, 2014 and 2017. In 2012, the reformed was related to reducing fixed tariffs, especially for solar energy, whilst in the 2014, the amendments were linked to change the fixed feed-in-tariffs in the market based renewable electricity prices. The 2017 amendment was made to change feed-in-tariff scheme to auctions scheme in order to encourage the investors to invest more in renewable energy sources.

In 2016, the Paris Agreement was ratified by the German government and later that year, Germany adopted the 'Climate Action Plan 2050', which was aligned with the Article 4 (19) of the Agreement. The Climate Action Plan 2050 stipulates long-term strategy for the development of low greenhouse gas emissions. The National Action plans is helpful in achieving the Paris Agreement targets to keep global warming below two degrees Celsius above pre industrial levels or even limit it to no more than 1.5 degrees Celsius above pre-industrial levels[1]. The Climate Action Plan 2050 duplicated the 2010 Energy Concept through the target segment for all sectors by 2030.

The Energiewende targets are shown in the table 2 below. (Source: Energy Concept)

Table 2: The Energiewende targets

Area	Indicator	2020	2030	2050
GHG emissions	GHG emissions reduction relative to 1990	-40%	-55%	-80-95%
Renewable Energy	RES share in final energy consumption	18%	30%	60%
	RES share in electricity consumption	35%	50%	80%
Energy Efficiency	Primary energy consumption reduction relative to 2008	-20%		-50%
	Gross electricity consumption reduction compared to 2008	-10%		-25%
	Final energy consumption in transport compared to 2005	-10%		-40%

2.1.2 Drivers of Germany's Energiewende

Climate change mitigation

Climate change mitigation is one of the main goals of Germany's Energiewende. The reduction of greenhouse gas emissions is also a part of Paris Agreement to limit the global temperature below two degree Celsius relative to pre-industrial level. The burning of fossil fuels releases the CO2 emissions and contributes to global

warming. Climate can be protected through reducing climate-damaging CO2 emissions, replacing fossil fuels supply to renewables and increasing energy efficiency.

In order to achieve the climate change mitigation objective, Germany adopted the Energy Concept law that set out three national targets for carbon reductions for the years 2020, 2030 and 2050. The CO2 emissions are to be reduced by 40%, 55% and 80-95% by 2020, 2030 and 2050, respectively compared to 1990 levels. In addition, recently, Germany has agreed to phase-out coal by 2038, as part of efforts to meet its climate goals.

Energy Security

Energy security is the important goal of Germany's Energiewende. Security of supply and reducing energy imports are two important drivers of energy security. Germany imports over 70% of oil, natural gas and coal to satisfy 50% of primary energy demand (IEA 2013). Renewable energy and energy efficiency are two pillars of Germany's Energiewende which can also help in achieving the energy security objective. The sustainable security of supply depends on the reduction of consumption of fossil fuels The increase in the share of renewables in the energy supply reduces dependence on imports of fossil fuels while energy efficiency helps in reducing the primary energy consumption. Germany aims to phase out nuclear power plants by 2022 and coal-fired power plants by 2038, something that will have significant impact on the country's energy security. Germany's energy security can only be maintained by increasing the renewable energy sources in the energy mix and electricity mix, and increase in energy efficiency. Therefore, Germany is investing heavily in renewable energy sources. For example, the share of renewables will increase to 35% and 80% of total electricity generation by 2020 and 2050, respectively. Similarly, primary energy consumption efficiency improves to 20% and 50% by 2020 and 2050, respectively.

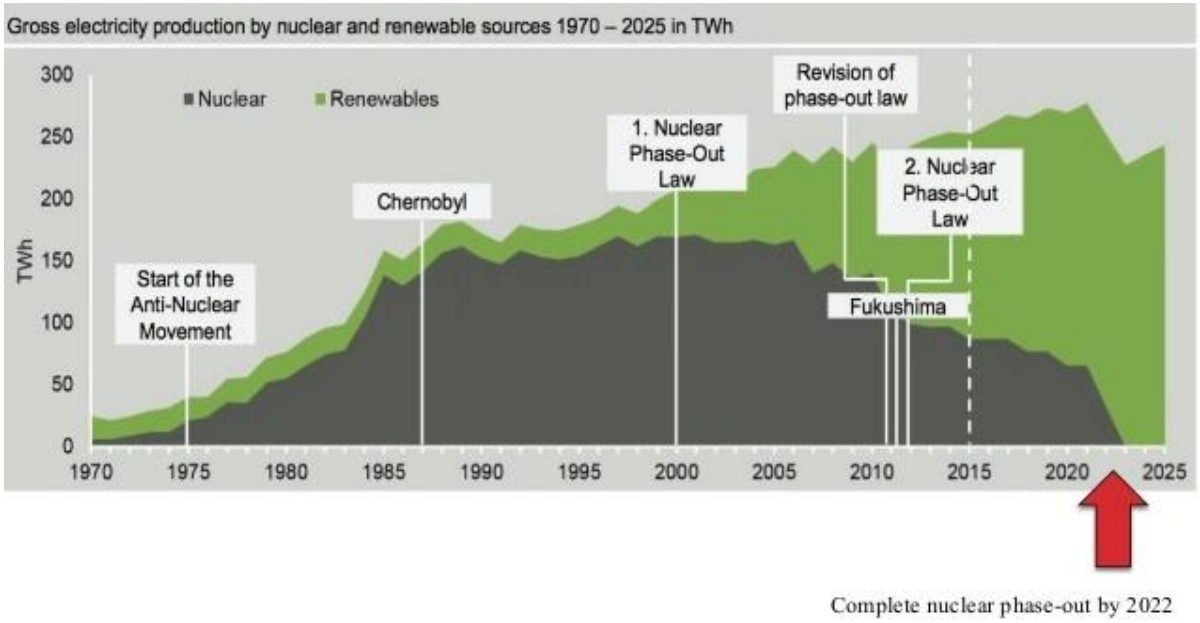


Fig.2 Germany's nuclear phase-out (Source: Energy Agency of the German state of Nordrhein-Westfalen)

2.2 Energy Transition in France

In Industrialized countries, France has a low-carbon electricity mix thanks to the large share of nuclear. France has immense legislative and policy measures to curb climate GHG emissions. Additionally, France has a comprehensive energy transition plan aligned with international climate goals.

The energy transition in France has started in 2015 after the adoption of law on Energy Transition for Green Growth. The law represents the end of a successful journey of National Debate on Energy Transition which began in 2012 with an aim to transform the French energy system. The Energy Transition Law is an integrated

climate and energy framework which defines national low carbon strategy, carbon budgets, a carbon price trajectory and energy investment planning[7].

2.2.1 Development of 'Energy Transition for Green Growth'

The roots of energy transition in France began in the 1970s after the oil crisis. Due to the oil crisis in 1973, the French government decided to take energy independence and move away from imported fossil fuels. Therefore, France opted to invest in nuclear power with the aim of reinforcing its energy independence and securing its supplies.

The energy transition officially began in France in 2015 after adopting the law on Energy Transition for Green Growth. Before the adoption of the 2015 law, there were several energy and climate policy instruments that set the tone for energy transition. The actual transition process began in 2005 when France ratified both the 1992 UN Conference on Environment and Development and the 1997 Kyoto Protocol, after which low-carbon energy policies were developed with an aim of reducing energy related. In the same year, a "Factor of four" or F4 was introduced in the energy policy with a goal of reducing 75% GHG emissions by 2050. In addition, in 2009 and 2010, the Grenelle laws addressed environmental and energy issues in the French energy policy with a focus on building and transport sectors (Law no 2009-967 and 2010-788).

In November 2012, a National Debate on Energy Transition was launched, which was a stakeholder consultation for a group of 120 experts. This parliamentary debate lasted for eight months (November 2012 – July 2013) with about 4000 amendments before giving the final shape[8]. The debate stipulated two main features: The Factor Four (F4) emission reduction target in 2050 (75% GHG emission reduction related to 1990) and curtail the nuclear power share in the electricity mix (75% to 50% in 2025 relative to 2015). However, the Factor Four (F4) was already established in 2005 and played a pivotal role in the French energy policy in 2012. The second feature of

[7] Energy policies of IEA countries – France 2016 Review
[8] Rüdinger, A. (2015). The French Energy Transition Law for Green Growth: At the limits of governance by objectives (Issue brief No. 07/2015). IDDRI.

reducing nuclear share in the electricity mix was introduced during this parliamentary debate.

In 2015, the National Debate on Energy Transition successfully passed as a law on Energy Transition for Green Growth Act. The Energy Transition for Green Growth Act established the National Low-Carbon Strategy (SNBC), which stipulated the reduction of greenhouse gas emissions by 75% until 2050 with an aim to transform French energy system towards sustainable and low-carbon economy[9]. It also sets out the series of carbon budgets for five year periods in 2015-18, 2019-23, and 2024-28. The Energy Transition Law was adopted in July 2015 a few months before France hosted the international climate conference COP21 in Paris. The COP21 not only provided the opportunity to promote the objectives of the France's energy transition prescribed in the law (including the transition towards a low-carbon economy while reducing GHG emissions and limit the rise in global temperature well below 2 degree Celsius), but also put France in the forefront to fight against climate change.

DEBATE, DEVELOPMENT AND PUBLICATION OF THE LAW	
November 2012 – July 2013	National debate on energy transition
October 2014	Draft legislation adopted by the National Assembly (lower house of the Parliament) and passed to the Senate for approval
October 2014 – July 2015	Several readings in the two chambers of French Parliament, leading to Senate approval
22 July 2015	Law adopted by French Parliament
18 August 2015	Following approval by the Constitutional Court, the law was published in the Journal officiel de la République Française
August 2015 – December 2015	Consultation and drafting process for implementation decree for Article 173 - this process included a formal consultation with investors and civil society groups, followed by a public consultation on the draft decree
31 December 2015	Implementation Decree for Article 173 was published

Table 3: Development of the Energy Transition Law (Source: French Energy Transition Law)

In 2017, a new 'Plan Climat' was introduced in the energy policy by the French minister under the framework of multi-year energy programme (PPE). The PPE

[9] Energy Transition For Green Growth Act in action: Regions - Citizens - Business

determines the energy objectives to be achieved for the public authorities through the priorities for action prescribed in the Energy Transition and Growth Act. The 'Plan Climat' introduced with an aim to phase out the coal power by 2022 and to achieve CO2 neutrality by 2050. The plan also sets a targets for the transportation sector including promoting electro-mobility and phasing- out the combustion engines vehicles by 2040.

2.2.2 Objectives and targets of Energy Transition Law

The Energy Transition for Green Growth Act adopted with the objectives to reduce GHG emissions, push for energy efficiency and diversification of energy supply in all the sectors. Additionally, the Act is committed to green economic growth with a target to increase GDP by 0.8% and 1.5% in 2020 and 2030, respectively and to create more than 75,000 jobs in housing sector.

The Energy Transition Law contains following quantitative and qualitative targets[10]:-

Quantitative targets

- ***Greenhouse gas emissions:***
    - Reduction of GHG emissions by 40% and 75% until 2030 and 2050, respectively relative to 1990 levels.
- ***Energy efficiency:***
    - Reduction of final energy consumption by 40% and 50% until 2030 and 2050, respectively relative to 2012.
    - The French building stock must perform in the Energy Performance Index (EPI) value as 80KWh/year/sqm until 2050
    - Thermal renovations need to be accelerated at a rate of 1.5% per year i.e. 5 lakhs dwellings

[10] Energy Transition For Green Growth Act, 2015

- ***Diversification of energy supply and renewables:***
    - Increase the share of renewables in total final consumption to 23% by 2030 and 32% by 2050. It also includes sectoral targets i.e. Heating- 38%, electricity- 40%, fuels- 15%, and natural gas- 10%.
    - Reduction of nuclear power share in total electricity generation from 75% to 50% by 2025
    - Reduction of fossil fuel share in primary energy consumption to 30% by 2030.
    - Phase out of coal power by 2022.

Qualitative targets and objectives

- To increase the energy independence and security of energy supplies
- Maintain the competitive prices of energy in the international markets
- Renovate the buildings and increase its energy efficiency
- Sustainable and clean transport
- To promote circular economy and minimize the waste
- To improve the nuclear safety
- To protect the human health
- To alleviate energy poverty

2.2.3 Drivers of Energy Transition Law

Climate change mitigation

France is making good progress to achieve its climate change mitigation goal. In three countries, France did exceptionally well in the Kyoto Protocol commitments for the period 2008-12. Additionally, France emitted less GHG in absolute terms in the last decade (OECD, National Accounts and Demography and Population Databases). France developed several climate and energy policies over the last decade which shows its commitment to climate change mitigation. First, in 2004, a climate plan developed that provides a framework for transitioning to a low-carbon economy, in which the policy measures of low-carbon energy production and

increase in efficiency of energy end-use sectors like building and transport were included. Second, a large number of carbon prices contained by various excise taxes on fossil fuels. Third, adoption of Energy Transition for Green Growth Act that includes targets of fighting against climate change. The Law contains ambitious targets of reducing GHG emissions (40% in 2030 compared to 1990), reducing fossil fuel and nuclear production, increasing the share of RES to 32%, and increasing the price of carbon.

Energy Security

France's energy mix is highly dependent on nuclear energy and has been invested heavily to guarantee its energy security. However, France is planning to decrease the nuclear share and coal-fired power plants will be closed by 2022 (Franco-German Energy Declaration 2018), which will have to be compensated by an increase in the share of renewable energy sources. In addition, France has also developed economic policies to promote renewable energy which will reinforce the security of supplies, create balanced energy mix and increase energy independence. POPE Act is one of the developments in this direction (POPE, No. 2005-781). The POPE Law defines not only the energy security objectives but also the climate protection objectives in France's energy policy. The Law also contains the objectives to increase the investments in renewable capacity through a Feed-In-Tariffs policy.

2.3 Energy Transition in the United Kingdom (UK)

At the beginning of the 21st century, the UK energy system was at a crossroads. Carbon emission reduction and security of supply were the main challenges for the UK energy system. To overcome these challenges, there was a need to transform the UK energy system. Eventually, this transition came in 2008 in the form of Climate Change Act[11]. Through this Act, the UK became the first country in the Europe to legislate a long-term target for reducing GHG emissions. Climate change mitigation and expansion of renewable energy sources are core elements of the Act.

[11] Climate Change Act, 2008. Chapter 27. The Stationary Office
Available at: http://www.opsi.gov.uk/acts/acts2008/ukpga_20080027_en_1S

2.3.1 Development of the Climate Change Act

The UK energy system has experienced a significant transformation since the 1980s. In the 80's, energy policy was not the major issue in the UK. There were several reasons including the UK energy independence from the resources of oil and gas in the North Sea, the sustainability of the world fossil fuel market, and the culmination of energy-related unions in power. In addition, the Department of Energy established in 1974 was also dissolved in 1992 (Strachan 2011). However, in the last two decades, the focus was again shifted to energy policy in response to energy supply challenges, global warming and the depletion of resources. In the 1980s, energy was secured through oil and gas resources in the North Sea, now due to decrease in oil and gas reserves in the North Sea has become a cause for concern. Also, due to the geopolitical instability in the OPEC countries, energy policy was reformed in the UK (BERR 2007).

The UK energy transition was primarily driven by the response of the IPCC report on the impacts of climate change (IPCC, 2005); a published report of "Stern review on the economics of climate change" (2006); and lobbying by several environmental NGOs. Initially, the main focus of this Act was climate change. However, with emphasis on security of supply as well as on affordability over time i.e. focused shifted to all the elements of energy trilemma. Additionally, an independent body was created as a "Committee on Climate Change" (CCC), which supported the low carbon transition plan through advising the government on system of carbon budgets to meet long-term emission targets (CCC, 2008). Eventually, the "Low Carbon Transition Plan" and the "carbon plan" were subsequently developed on transition towards a low-carbon economy through setting out decarbonisation targets for 2050 (DECC, 2009; 2011)

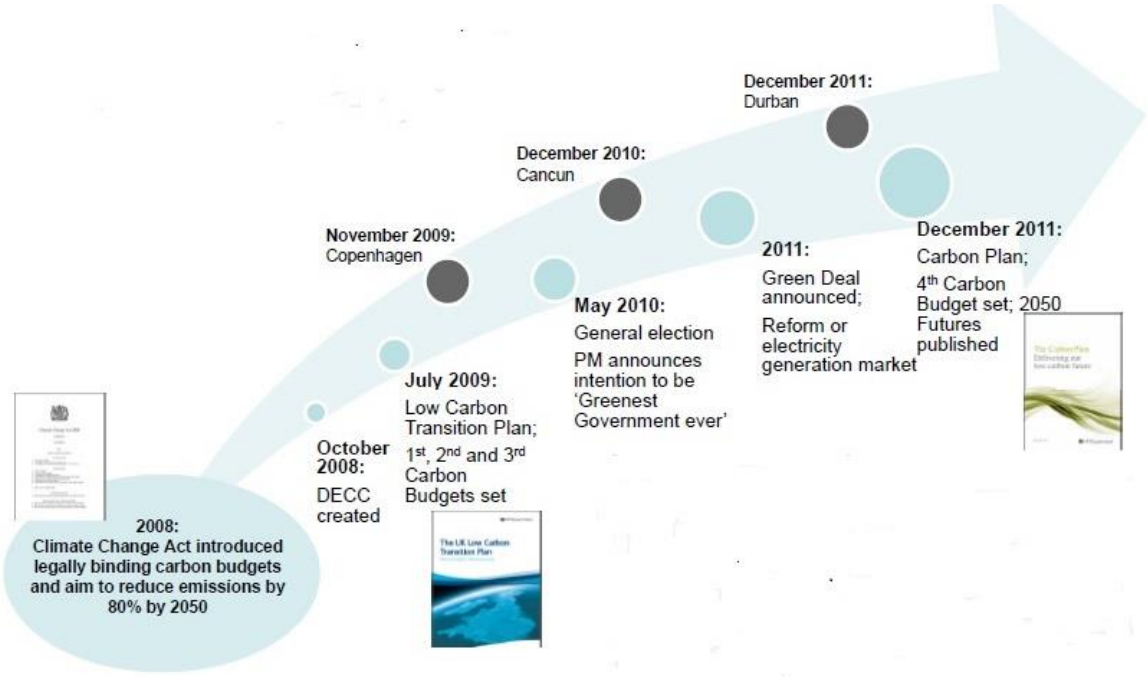


Fig.3 Development of the Climate Change Act (Source: DECC)

In recent times, the UK government has made several policy changes on energy supply including decision on phase-out of coal-fired power plants by 2025; expansion of renewable energy sources, particularly offshore wind was strongly promoted in 2016; and the Committee on Climate Change (CCC) advises the Department of Energy and Climate Change (DECC) on emissions policy i.e. for the fifth carbon budget (2028-2032) carbon emissions need to reduce 57% by 2030 compared to 1990 level.

2.3.2 The Climate Change Act, 2008[12]

The Climate Change Act is a long term policy commitment to reduce GHG emissions between 2009 and 2050. This Act is a major step to tackle climate change while ensuring the UK government to meet its carbon reduction targets.

[12] T. L. Muinzer, 2019. *Climate and Energy Governance for the UK Low Carbon Transition*

The key provisions of this Act include:

- Establishment of a long term greenhouse gas emission reduction targets – 34% reduction by 2020 and 80% reduction by 2050 compared to 1990 level.

- Establishment of 5 year carbon budgets – A series of 5 year decarbonisation trajectory " carbon budgets" were developed for a period of 2008- 2050. Since then five carbon budgets have been proposed: The first budget (2008-12); second budget (2013-17); third budget (2018-22); fourth budget (2023-27); fifth budget (2028-32).

- Establishment of a Committee on Climate Change (CCC) – The CCC is an independent statutory body providing advice to the government for achieving decarbonisation targets. The CCC comprises experts of climate change scientist, technologists and economists.

2.3.3 Drivers of the Climate Change Act

Climate change mitigation

Energy security is one of the main components of energy policy, but not at the expense of climate change. The IPCC also confirmed through its scientific report that decarbonising the energy sector is essential because burning of fossil fuels is responsible for climate change. Recognizing the importance of decarbonising the energy system, the UK government revised the long-term ambitious GHG emission reduction target from 60% to 80% by 2050 compared to the 1990 levels (CCC, 2008). These targets are embodied in the Climate Change Act (2008) that stipulates 80% reduction in carbon emissions below 1990 levels by 2050. Additionally, five-years of carbon budgets were formulated to implement these targets. Subsequently, Low Carbon Transition Plan (2009) and Carbon Plan (2011) targets were introduced to curb carbon emissions. The Low Carbon Transition Plan not only describes 34% carbon emission reduction from 1990 levels by 2020, but also 40% electricity

generation from low carbon sources by 2020, of which 30% from renewables (DECC, 2009).

Besides the Climate Change Act targets, several other climate change mitigation targets were agreed for the reduction of carbon emissions. First, the Kyoto Protocol, where the UK agreed to reduce the GHG emissions by 12.5% compared to 1990 levels for the period between 2008 and 2012. Second, under the European Union (EU) carbon reduction target, the UK agreed to cut 20% carbon emissions by 2030 compared to 1990 levels. There were two key drivers for the reduction of GHG emissions in the UK energy system – switching from coal to natural gas in the electricity mix; and deindustrializing the economy that shut down energy-intensive manufacturing industries in the UK (Bradshaw 2010).

The UK government also introduced fiscal instruments to reduce carbon emissions such as disincentivize the carbon-based energy and incentivize the clean and renewable energy. Climate Change Levy (CCL), Emission Trading Scheme (ETS), and Carbon Floor Price (CFP) were three main emission taxes which were introduced in 2001, 2005 and 2013, respectively. Carbon Taxes on carbon emissions were introduced with the aim of reducing carbon emissions while penalizing carbon polluters. It is defined as “an excise tax imposed according to the carbon content of fossil fuel and is thus restricted to carbon-based fuels only” (Pearce 2006).

Energy Security

The UK was secured with fossil fuel energy resources thanks to the reserves of coal, oil and natural gas. It could also be seen in the UK energy mix which was dominated by natural gas, oil and coal. Also, as per the UK’s geographic location it has potential to generate energy from renewable energy sources of wind, sun, biomass, waves and tides. However, due to depletion of resources and the fast approaching date for decommissioning old plants, energy security became an issue in recent times (DECC 2010). In addition, once a large exporter of natural gas the UK has now become a major importer. To overcome these challenges, there was a need to emphasize the UK’s energy policies that provide not only a secure but also the low

carbon and affordable energy system. These challenges forced the UK government to reconsider its energy policy. The UK government has revived the energy policy considering : 1) increase the share of nuclear in the energy mix, and 2) maximize the recovery of oil and gas from the North Sea and on-shore hydraulic fracking (DECC 2015b). Additionally, the UK government made a significant progress to support and promote the expansion of renewable energy in the energy system, including the Renewable Energy Strategy (2009), which was developed under the Low Carbon Transition Plan. Simultaneously, the UK government introduced Renewables Obligation (RO), Contracts for Difference (CfDs) and Feed-in-Tariff scheme to promote renewable energy.

CHAPTER 3

ANALYTICAL TRANSITION FRAMEWORK

The chapter analysis the historical decarbonisation trends of Germany, France and the United Kingdom. This chapter examines the historical patterns of energy supply and energy use in all three countries. Additionally, it also provides the comparison and analysis of historical energy transitions between Germany, France and the UK.

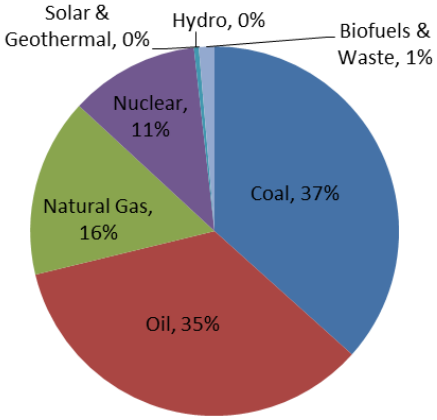
The historical trends have been analysed between 1990 and 2015 considering the following elements:-

- Energy supply side
- Energy demand side
- Energy security – Security of supply
- Climate change mitigation - CO_2 emission reduction
- Renewables in electricity generation

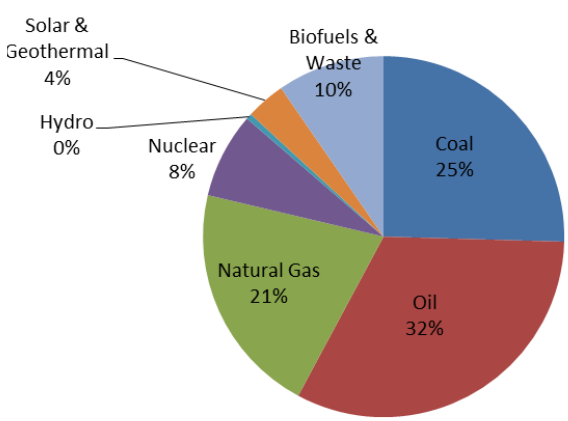
3.1 Historical decarbonisation trends of Germany

This part analysis the historical decarbonisation trends of Germany. The table 4 and fig. 4 & 5 compare the main characteristics of Germany's energy sector in 1990 and 2015.

Fig. 4 Total Primary energy supply (TPES) – Germany (Data source: IEA)



1990



2015

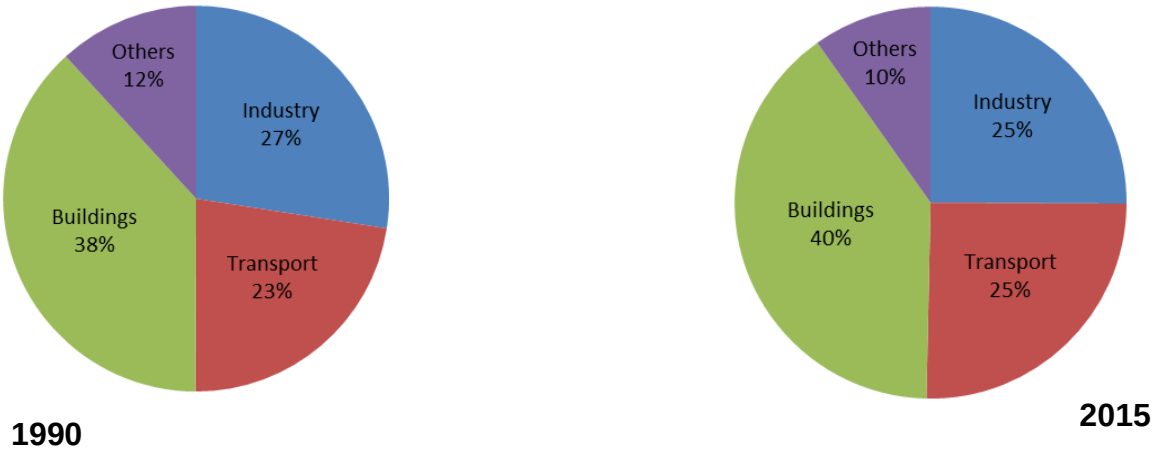


Fig. 5 Total final consumption (TFC) – Germany (Data source: IEA)

Table 4: Main characteristics of Germany's energy sector (Data source: IEA)

Indicators	1990	2015
Population (millions)	79	82
Total Primary Energy Supply (TPES) (Mtoe)	351	308
Total Final Consumption (TFC) (Mtoe)	240	220
Energy production (Mtoe)	186	120
Net imports (Mtoe)	167	198
CO2 emissions from fuel combustion (MtCO2)	940	730
Renewable electricity generation (TWh)	20	143

3.1.1 Energy supply side

The total primary energy supply (TPES) of Germany has decreased from 351 Mtoe to 312 Mtoe in 2015 compared to 1990, representing 12% fall in 2015. In 2011, Germany's total primary energy supply reached at lowest level that amounted for 311.8 million tonnes of oil equivalent (Mtoe). The total primary energy supply is gradually declining from 2001 when it totaled to 346.6 Mtoe and has decreased by 10% since then.

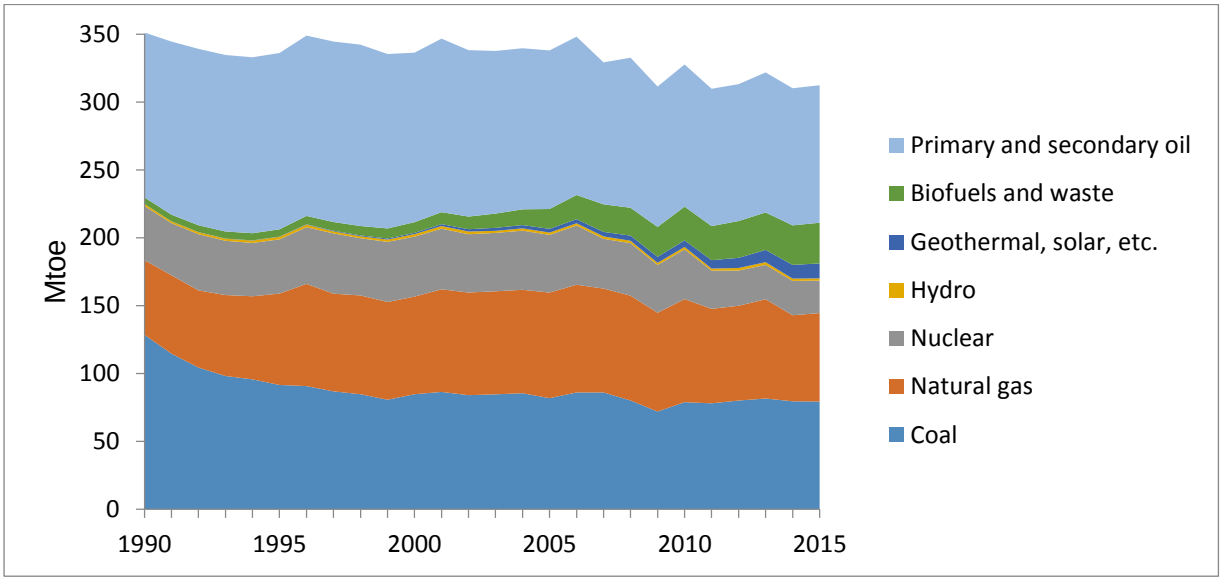


Fig. 6 Total Primary Energy Supply (TPES) by source- Germany, 1990-2015 (Data source: IEA)

Oil is the largest fossil fuel energy source followed by coal and natural gas. In 2015, oil accounted for 32% of fossil fuel energy, whilst coal and natural gas accounted for 25% and 20% of fossil fuel energy, respectively. In 2010, oil amounted to 104.7 Mtoe, represented 32% of the TPES. However, since then, oil supply has gradually declined but still contributed the largest share of TPS in 2015. The share of coal in the TPES has also declined from 128.59 Mtoe to 79.4 Mtoe in 2015 relative to 1990. Although Germany is one of the largest producers of coal, the German government has recently decided to stop the production of coal by 2038 (Energiewende). The share of natural gas in the TPES has increased from 54.98 Mtoe to 65.15 in 2015 compared to 1990.

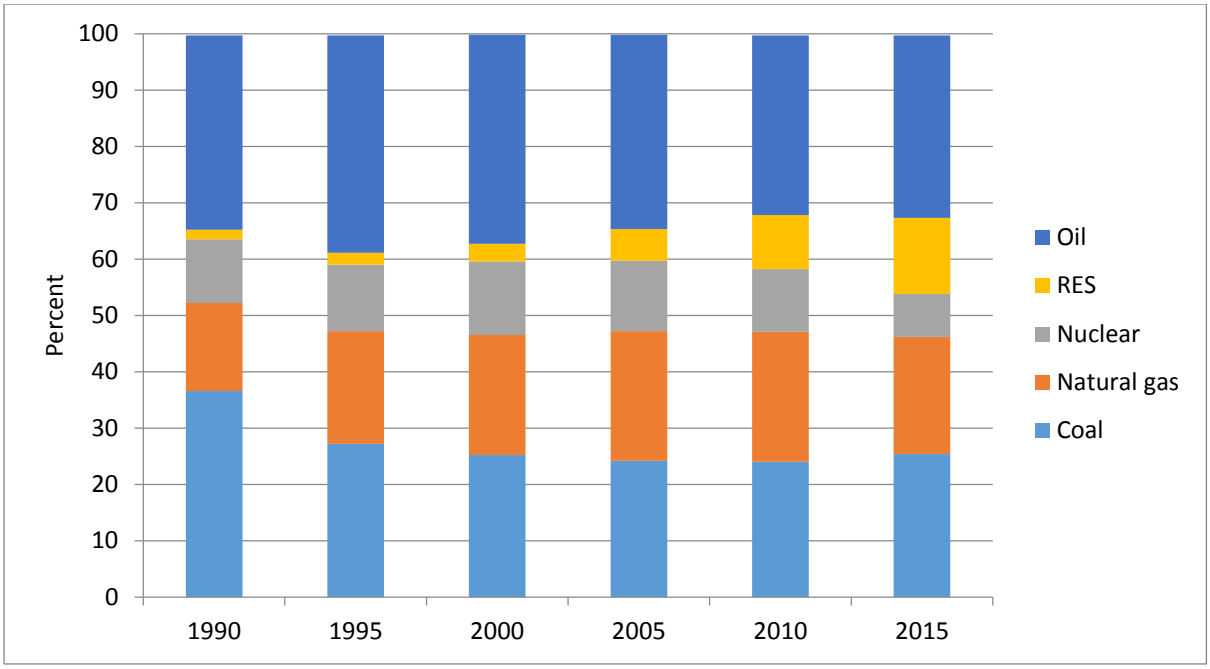


Fig. 7 Fuel shares in primary energy – Germany, (Data source: IEA)

Energy from renewable energy sources has increased from 1.7% to 13.5% in 2015 compared to 1990; making it the most important non-fossil energy source, 9.5% of which came from biofuels. Biofuels amounted to5 Mtoe in 1990, which increased six-fold in 2015. The other renewables, particularly solar has increased from negligible to 3.5 %, amounted to 11 Mtoe in 2015.

Nuclear is also the cleanest form of energy, however, nuclear energy has fallen from 11.7% to 7.6% in 2015 compared to 1990. This is because the German government has decided to shut down all nuclear reactors by 2022 after the Fukushima nuclear disaster (Energy Concept).

3.1.2 Energy demand side

The fig. 8 indicates that Germany's total final consumption (TFC) has decreased from 240.7 Mtoe to 220.1 Mtoe in 2015 relative to 1990; representing 10% fall in 2015. In 2009, the total final consumption has reached the lowest level due to the global financial crisis, where it amounted to 214 Mtoe.

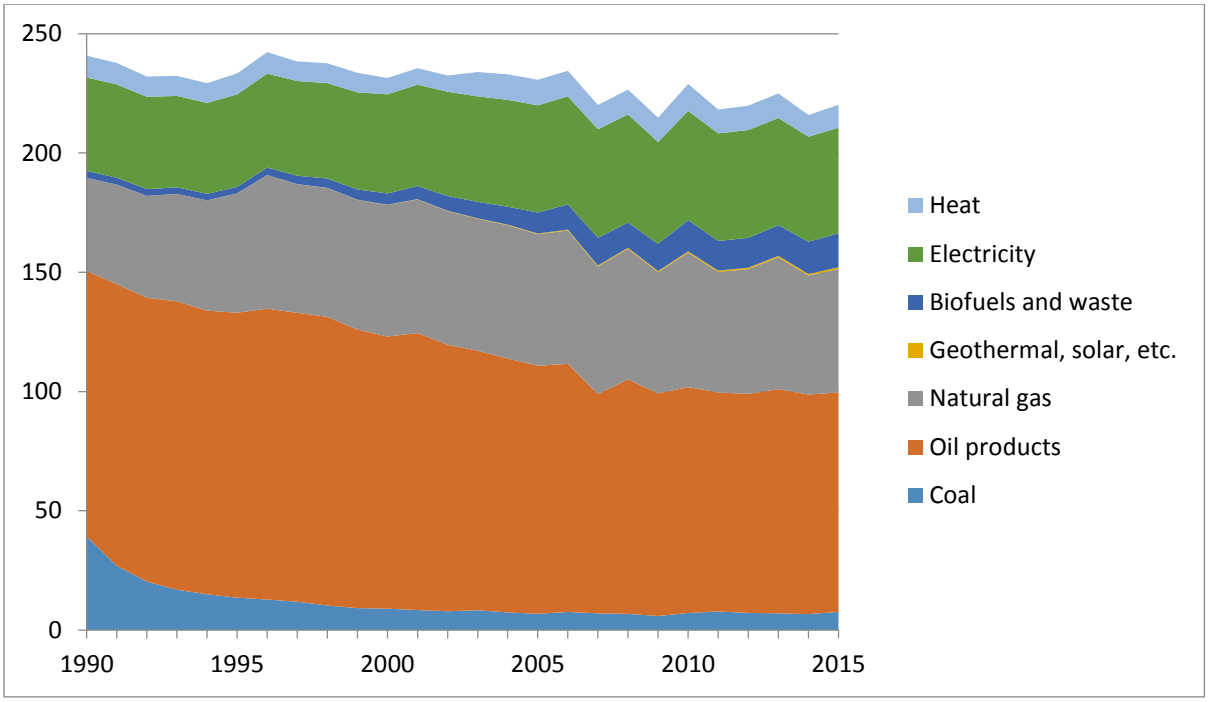


Fig. 8 Total Final Consumption (TFC) by source - Germany, 1990-2015 (Data source: IEA)

Germany relies heavily on fossil fuels to meet its demand, where oil products are the largest energy source consumed, followed by natural gas. However, between 1990 and 2015, Germany oil products demand fell from 46% to 41% in 2015 relative to 1990. At the same time, Germany natural gas demand has increased from 16% to 24% in 2015. Due to the global economic crisis and milder winter weather conditions, natural gas demand decreased significantly in 2009 and 2011. Electricity use in final consumption has increased from 16% to 20 % in 2015 compared to 1990. The renewable energy sources including solar and biofuels contributed only 7% in the final energy consumption in 2015.

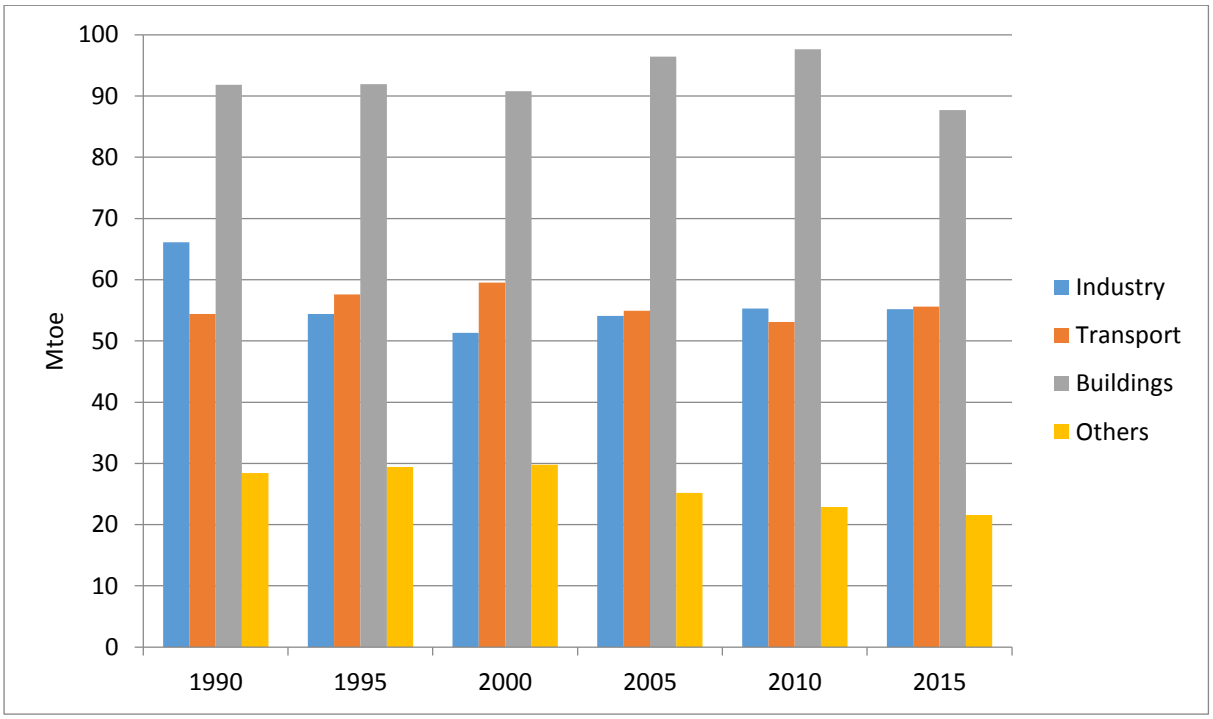


Fig.9 Total Final Consumption (TFC) by sector – Germany, (Data source: IEA)

The building sector is the largest energy end-use sector followed by transport and industry. However, the transport sector has emerged as the fastest growing sector in 2015. The industry was the second largest energy end-use sector until 2010, but due to the increase in the population of Germany, the demand for transport has also increased, resulting in the transport sector has surpassed the industry sector in final energy consumption in 2015.

The final energy consumption in the building sector has decreased from 91.8 Mtoe to 87.8 Mtoe in 2015 compared to 1990. This is because the energy efficiency in buildings has improved. Germany has established and implemented robust building energy efficiency policies, which has resulted in a decrease in the final energy consumption of buildings. The industry sector final energy consumption has also decreased from 66.1 Mtoe to 55.2 Mtoe in 2015 compared to 1990, representing 17% decline in 2015. The transport sector demand has marginally increased from 54.4 Mtoe to 55.6 Mtoe in 2015 compared to 1990.

3.1.3 Energy security – Security of supply

Import dependency is one of the indicators of energy security. Germany's import dependency has increased by 16% in 2015 compared to 1990. In 1990, net energy import accounted for 167.29 Mtoe, which has increased to 198.32 in 2015. The import dependency has increased due to the imports of oil and natural gas. Germany has imported natural gas from Russia, Norway and the Netherlands (IEA 2013). However, between 1990 and 2015, there was no significant change in the net imports of oil, while net import of natural gas increased two-fold during this period. Simultaneously, export of gas has also increased in this period. Since 1990, the export of gas has increased significantly from 1 Mtoe to 30 Mtoe in 2015.

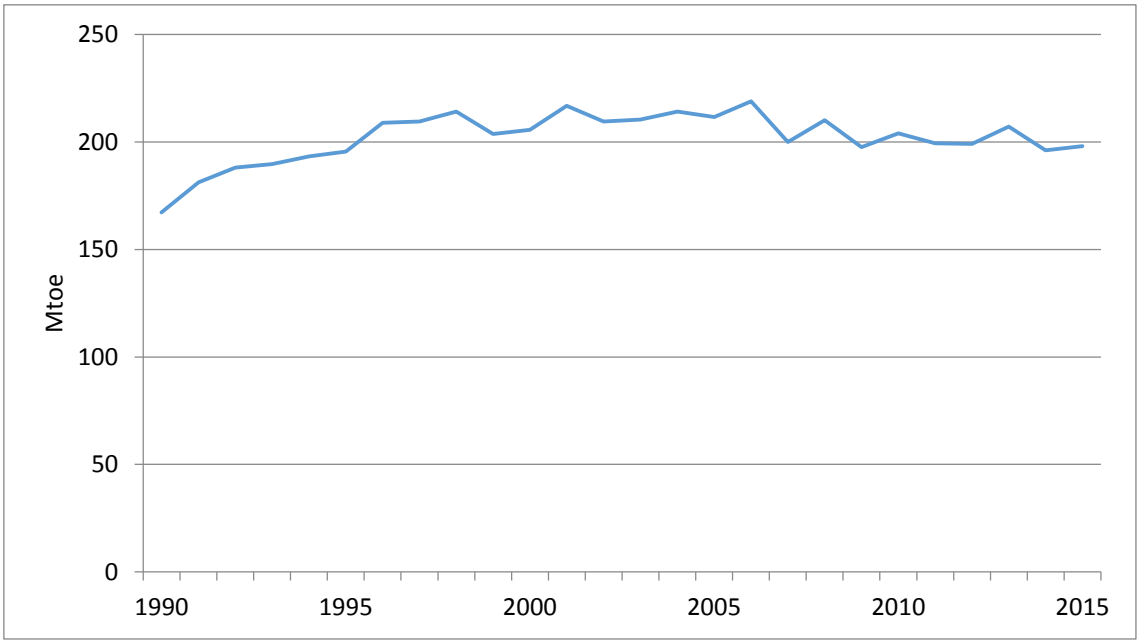


Fig. 10. Net energy imports – Germany, 1990-2015 (Data source: IEA)

In security of supply, infrastructure plays an important role and it is important for Germany due to its high dependence on oil and gas imports. Germany has a good infrastructure of oil supply that includes pipelines of crude oil and oil product as well as import terminals. There are four oil importing ports, three of which are located in the North Sea and the fourth on the Baltic Sea. Additionally, Germany has total eight pipelines which are both cross-border and domestic pipelines. The oil-tank storage facilities have a capacity of 65.7 million cubic meters (mcm) which are well distributed in the Germany (IEA 2013).

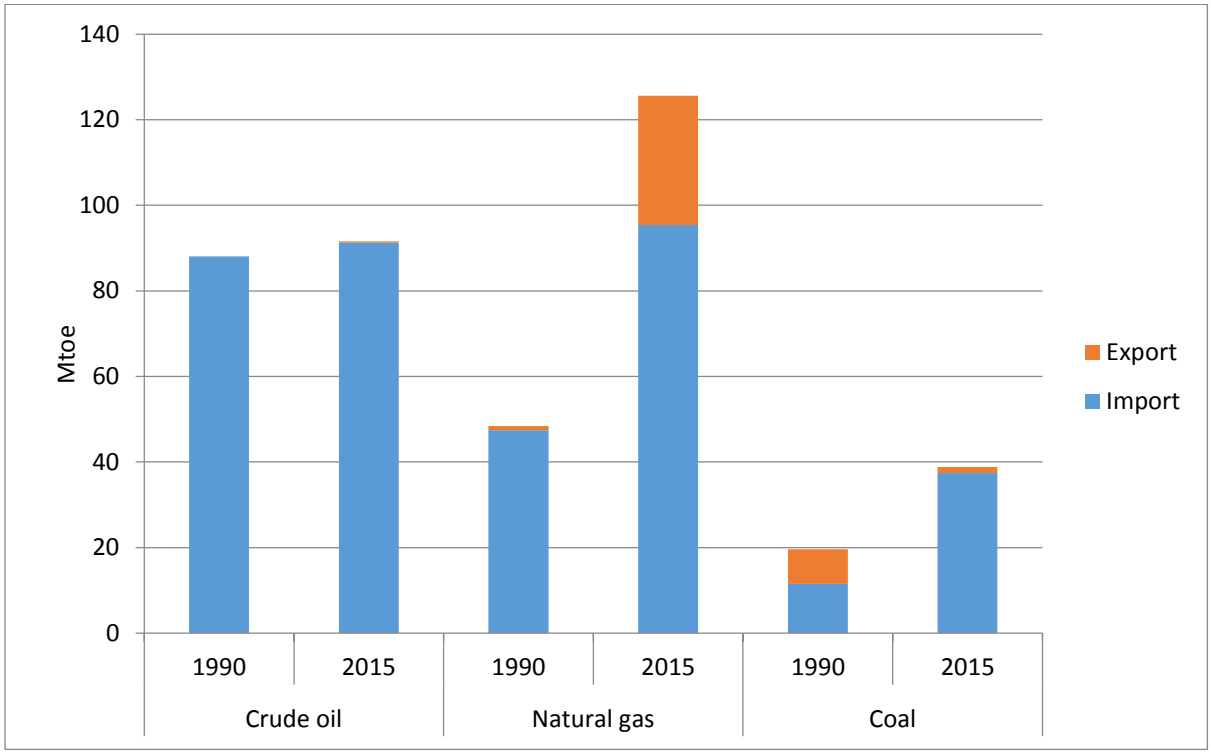


Fig.11 Energy import-export – Germany, (Data source: IEA)

In addition, Germany also has a robust natural gas infrastructure with the largest gas storage facility in Europe .There are 48 natural gas storage facilities with a total capacity of 20.9 billion cubic meters (bcm). Germany has cross-border connections with a massive pipelines network. However, because of no liquefied natural gas (LNG) infrastructure, Germany is dependent on neighbouring countries to use their LNG terminals (IEA 2013).

3.1.4 Climate change mitigation - CO2 emissions reduction

Decarbonisation effort of a country can be recognized through its potential of CO2 emissions reduction. On one hand, fig. 12 indicates that Germany has moved positively to meet its decarbonisation objectives as CO2 emissions were reduced significantly by 23% in 2015 compared to 1990. In 1990, total CO2 emissions amounted for 940 MtCO2, which fell to 729 MtCO2 in 2015. On the other hand, it

indicates that since the last decade Germany is more dependent on fossil fuels to meet its needs. This is because progress on reduction in CO2 emissions has slowed down and in 2015 emissions declined only by 7.3% relative to 2005. In 2005, CO2 emissions accounted for 786 MtCO2, which slightly decreases to 729 MtCO2 in 2015. During a decade of 1990's, CO2 emissions reduced on average 1.7% per annum, which was slowed down between 2000 and 2005 and decreased on the average of 0.7% per annum, then after 2005 , emissions declined about 7% in 2015. Between 2009 and 2011 emissions went down due to economic crisis, but after 2011 emissions increased again for two years due to the improvement in economy, and then again went down by 2015.

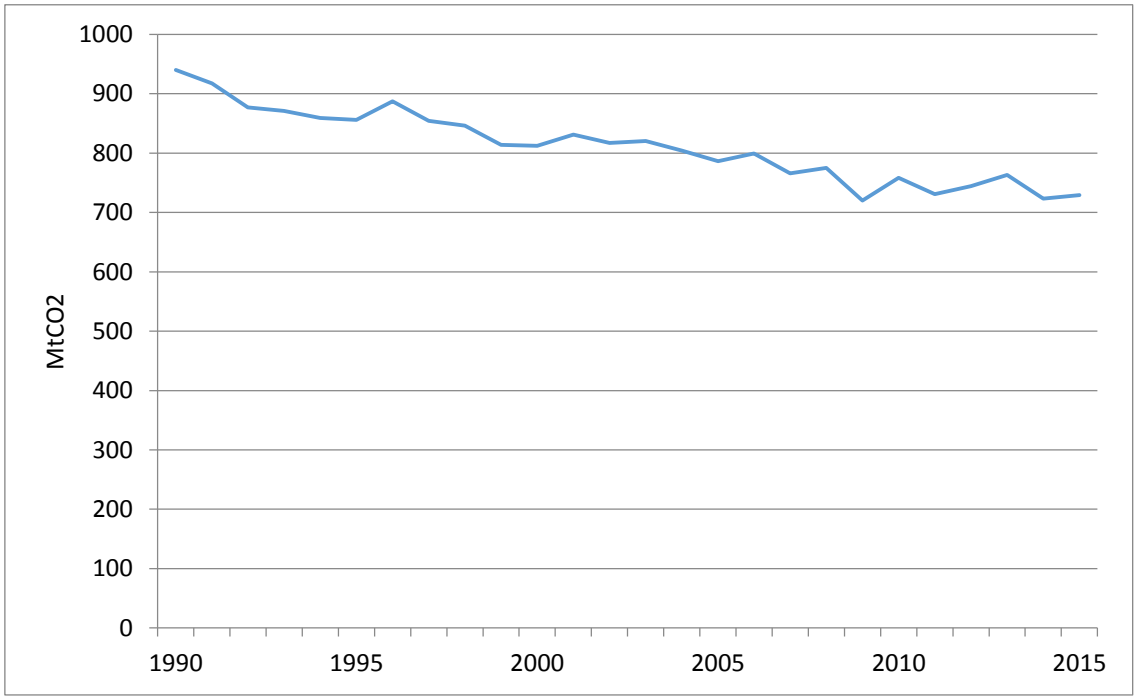


Fig.12 Annual CO2 emissions – Germany, 1990-2015 (Data source: IEA)

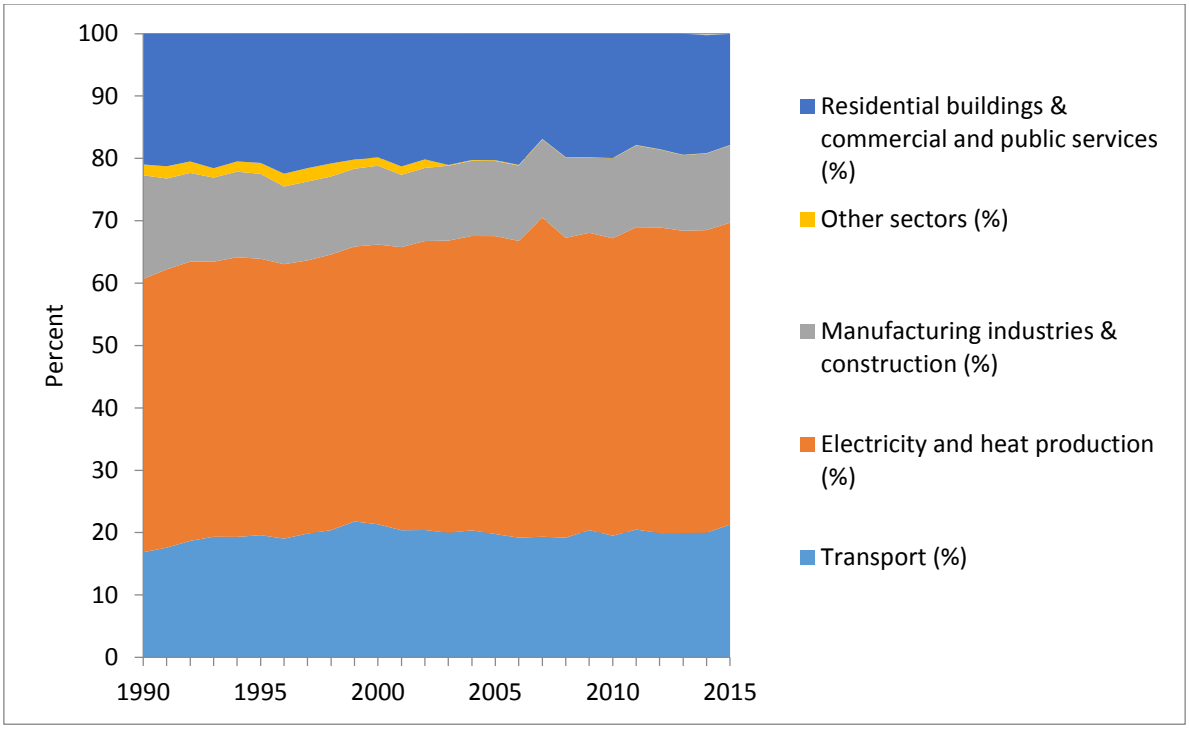


Fig.13 CO2 emissions by sector-Germany, 1990-2015 (Data source: IEA)

The fig.13 shows historical CO2 emissions by sector from 1990 to 2015. Electricity sector accounted for largest share of greenhouse gas emissions followed by transport, buildings and industry sectors. This indicates that the largest share of fossil fuels consumed by the electricity sector and transport sector.

Electricity and heat sector accounted for 48% of total CO2 emissions in 2015, increased by 10% since 1990, which was driven by extensive use of coal in the electricity production. Coal has high CO2 emission factor that produces high amount of CO2 emissions. CO2 emissions from transport sector increased from 16% to 21% in 2015 compared to 1990. Oil is the main source of transport sector and road transport is the largest source of CO2 emissions in Germany. Most vehicles are diesel – powered vehicles which produces more emissions than petrol vehicles. In contrast to electricity and transport sector, emissions from buildings and industry sector declined in 2015 relative to 1990. Building sector including residential and commercial buildings accounted for 21% of CO2 emissions, representing 18% decline in 2015 due to the adoption and implementation of energy efficiency policies. Industry sector also reduced their emissions from 16% to 12% in 2015. This was

driven by energy efficiency in the industry and some of the industries have moved to other countries (Energiewende).

3.1.5 Renewables in electricity generation

Renewable energy and electricity are two important drivers for energy transition, and electricity generation from the renewables is the most important driver for decarbonisation. Germany has also increased the renewables in its electricity mix in order to decarbonize its energy system.

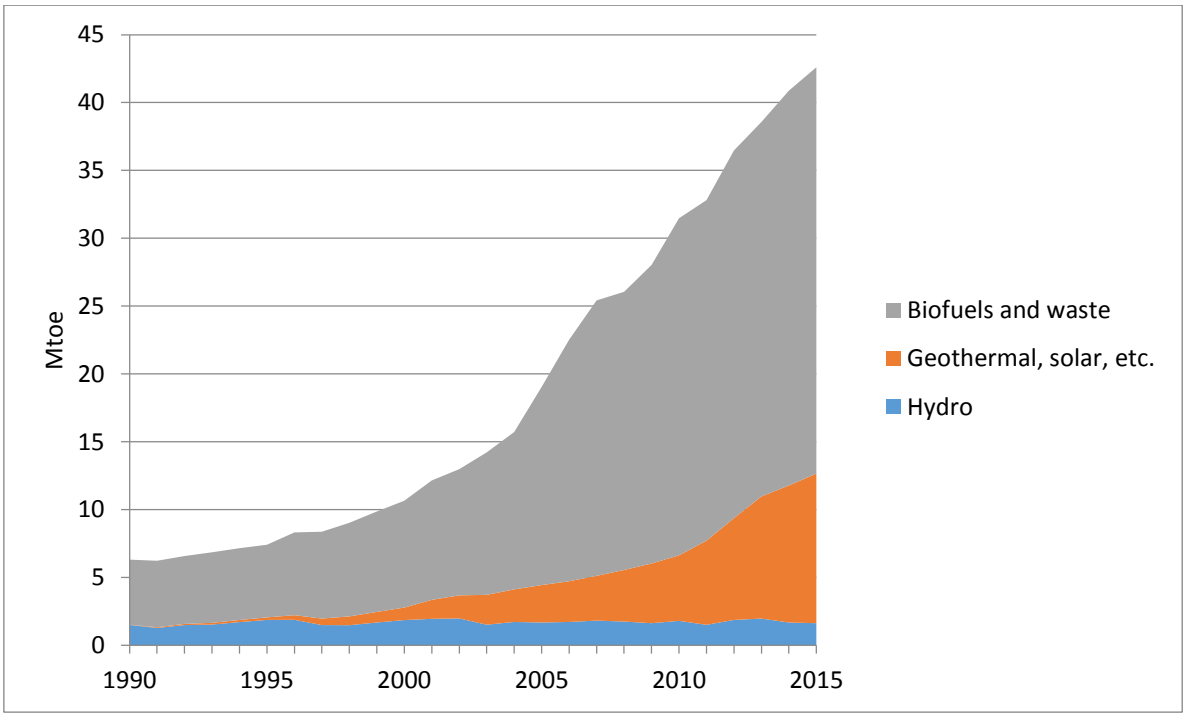


Fig.14 Renewable energy in total primary energy supply – Germany, 1990-2015 (Data source: IEA)

The fig.14 shows that penetration of renewables in the TPES has progressed slowly and increased seven-fold from 6 Mtoe to 42 Mtoe in 2015 compared to 1990. Biofuels and waste made a large contribution, which increased six-fold in 2015 compared to 1990. Biofuels and waste accounted for 5 Mtoe in 1990, which increased to 30 Mtoe in 2015, represented 71% of total renewable energy sources. Solar renewables has increased significantly 11-fold from negligible to 11 Mtoe in 2015 relative to 1990. Hydro renewables contributed least in the renewable energy sources and the trend was quite stable. Hydro accounted for 1.48 Mtoe in 1990 and increased marginal to 1.63 Mtoe in 2015.

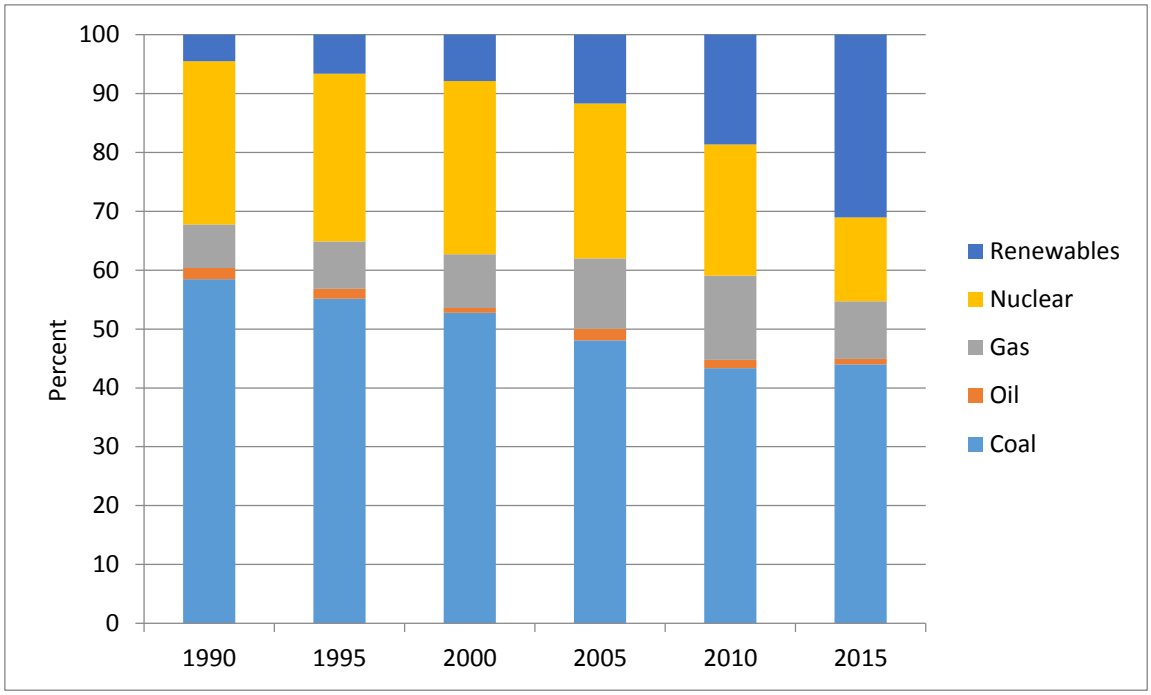


Fig. 15 Electricity generation by fuel – Germany, (Data source: IEA)

The fig.15 shows electricity generation by fuel from 1990 to 2015. The share of fossil fuels in the electricity generation has reduced from 67% to 54% in 2015 compared to 1990. Coal and oil share of fossil fuels has decreased, whilst share of natural gas in the electricity generation has increased in 2015. The share of coal reduced from 58% to 44% whereas Oil share reduced half from 1.8% to 0.9% in 2015 relative to 1990. The share of natural gas has increased from 7.3% to 9.7% in 2015 compared to 1990. The interesting point is the natural gas share has increased from 7.3% to 14.3% in 2010; thereafter it reduced sharply to 9.7% in last five years. The nuclear power, which is known as clean power, also reduced to half in 2015.Nuclear amounted for 28% in 1990, which reduced to 14% in 2015. The nuclear power has increased until 2000, and then started to decline slowly by 2011, but after the Fukushima nuclear accident nuclear share declined rapidly. Renewables has progressed swiftly from 4.5% to 31% in 2015 compared to 1990. The renewables has increased rapidly after 2011 after the German government made a decision to shut down the nuclear power and renewable was seen as cleaner energy alternatives to nuclear.

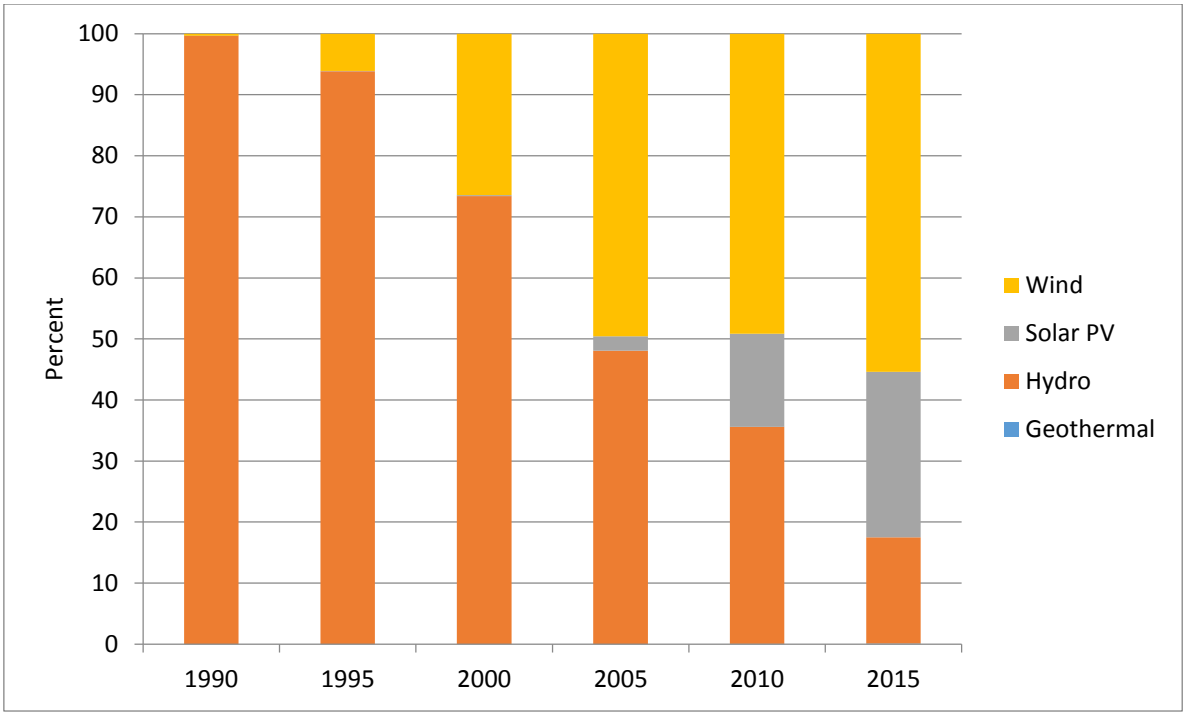


Fig.16 Electricity generation from renewables by source – Germany (Data source: IEA)

Hydro was the main source of renewables for an electricity generation in 1990s. In 1990, hydropower made up almost 100% of electricity produced in Germany with negligible contribution from other renewables. In 2000, the hydropower share decreased to 3/4th and remaining quarter was replaced by wind power. In 2005, the hydropower share reduced to almost half and the remaining half contributed from wind for the electricity generation. In 2015, hydropower share fell to lowest 17%, wind share increased by 5 points and represented 55% of total renewables in electricity generation. The remaining 27% share was contributed by solar PV, which has penetrated into the electricity generation since 2000.

3.2 Historical decarbonisation trends of France

This part analysis the historical decarbonisation trends in France between1900-2015. The table 5 and fig 17 & 18 compares the main characteristics of France's energy sector in 1990 and 2015

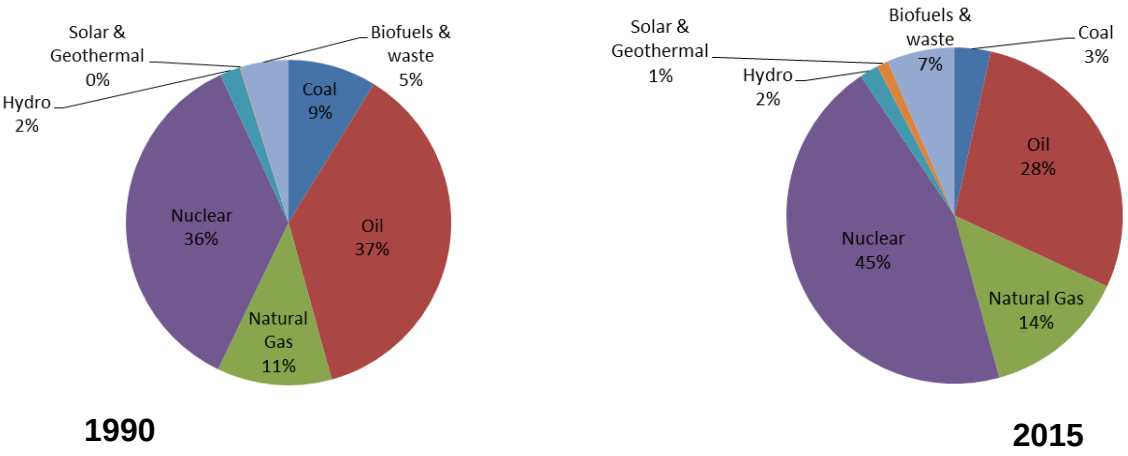


Fig. 17: Total Primary energy supply (TPES) – France (Data source: IEA)

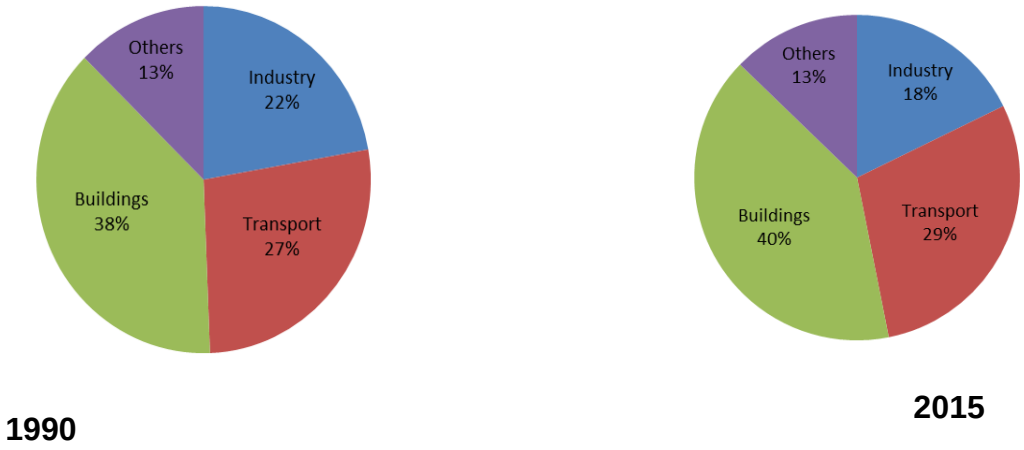


Fig. 18 Total final consumption (TFC) – France (Data source: IEA)

Table 5: Main characteristics of France's energy sector (Data source: IEA)

Indicators	1990	2015
Population (millions)	58	67
Total Primary Energy Supply (TPES) (Mtoe)	224	249
Total Final Consumption (TFC) (Mtoe)	142	150
Energy production (Mtoe)	112	139
Net imports (Mtoe)	119	117
CO2 emissions from fuel combustion (MtCO2)	346	292
Renewable electricity generation (TWh)	58	88

3.2.1 Energy supply side

France's total primary energy supply (TPES) increased from 227 Mtoe to 253 Mtoe in 2015 compared to 1990, representing 10% increase in 2015. The TPES has reached the highest level in 2005, where it amounted to 277 Mtoe, since then it has declined 8.5% by 2015. Nuclear was the largest energy source of TPES followed by oil in 2015, where nuclear represented 44.8% of TPES and oil represented 28.4% of TPES in 2015. Nuclear share has increased 29% of TPES whereas oil share has declined 14% of TPES in 2015 compared to 1990.

Fossil fuels represented 45.7% of total primary energy supply followed by nuclear and renewables, which represented 44.8% and 9.5% of TPES, respectively in 2015. Oil was the largest fossil fuel energy source and amounted to 28.4% of TPES in 2015. Natural gas and coal amounted to 13.7% and 3.5% of TPES, respectively. Since 1990, fossil fuel share has decreased from 57% to 45.7%, whilst renewables share has increased from 6.7% to 9.5% in 2015.

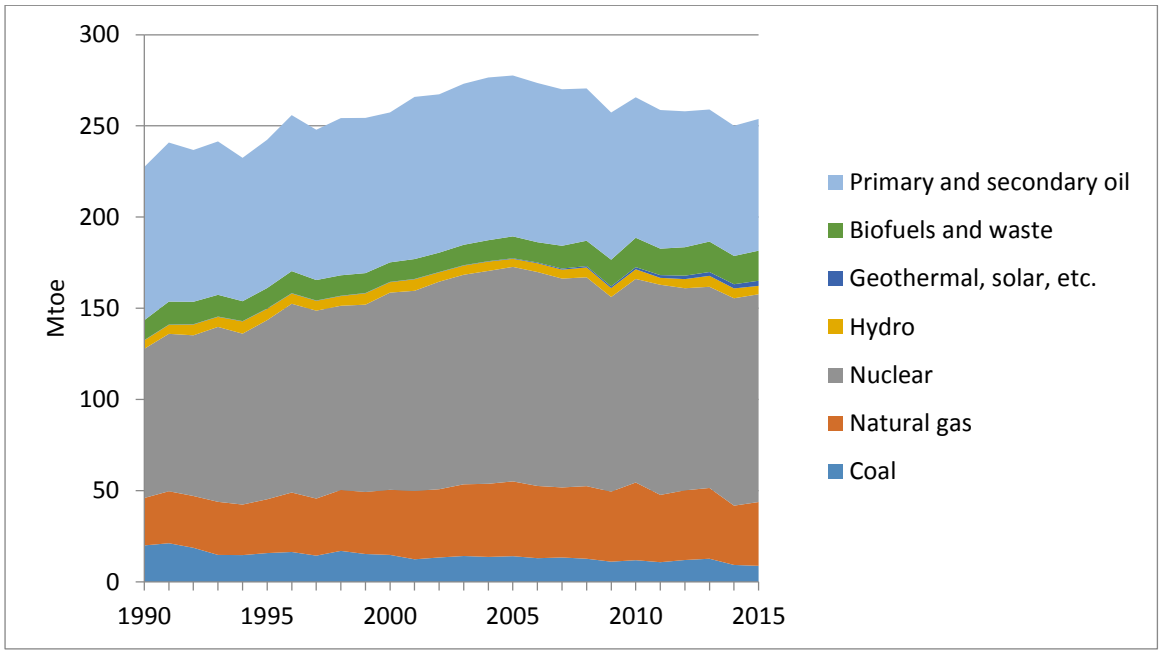


Fig. 19 Total Primary Energy Supply (TPES) by source – France, 1990-2015 (Data source: IEA)

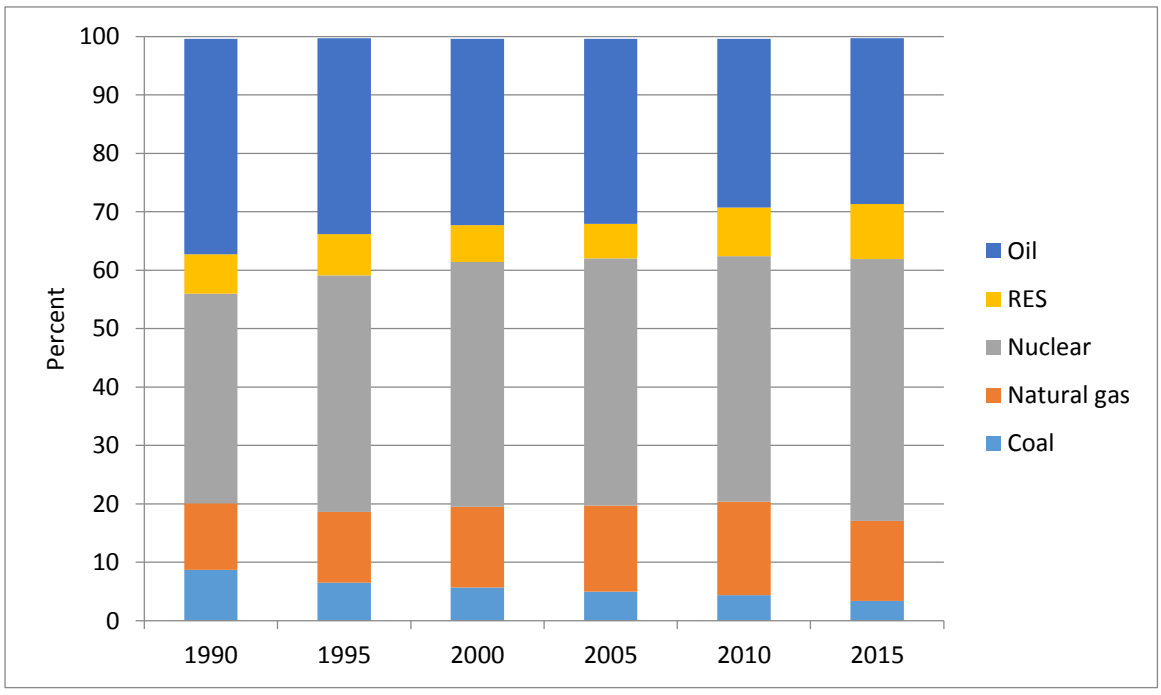


Fig. 20 Fuel shares in primary energy – France (Data source: IEA)

More than half of the total primary energy supply of France came from clean fuels in the form of nuclear and renewables. Nuclear accounted for 82 Mtoe in 1990, which has increased to 114 Mtoe in 2015. Between 1990 and 1996, nuclear supply has risen sharply and reached 104 Mtoe, representing 20% increase in 6 years. Since then, nuclear supply has slowly increased, representing only 10% rise in 19 years. The renewable growth was also steady, which increased from 15.5 Mtoe to 24 Mtoe in 2015 compared to 1990. The share of renewables of TPES has increased from 6.2% to 9.5% in these 25 years. Biofuels and waste contributed the highest share of renewables of TPES and amounted to 17 Mtoe in 2015. Hydro supply has remained stable all these years and amounted to 4.6 Mtoe in 2015. Solar energy supply has increased from negligible to 3 Mtoe in 2015.

3.2.2 Energy demand side

France's total final consumption (TFC) from fuel supply has increased from 141 Mtoe to 150 Mtoe in 2015 compared to 1990, representing 6% increase by 2015. In a recent decade, France TFC from fuel source reached the highest level in 2004 and the lowest level in 2014, where it amounted for 168 Mtoe and 147 Mtoe, respectively.

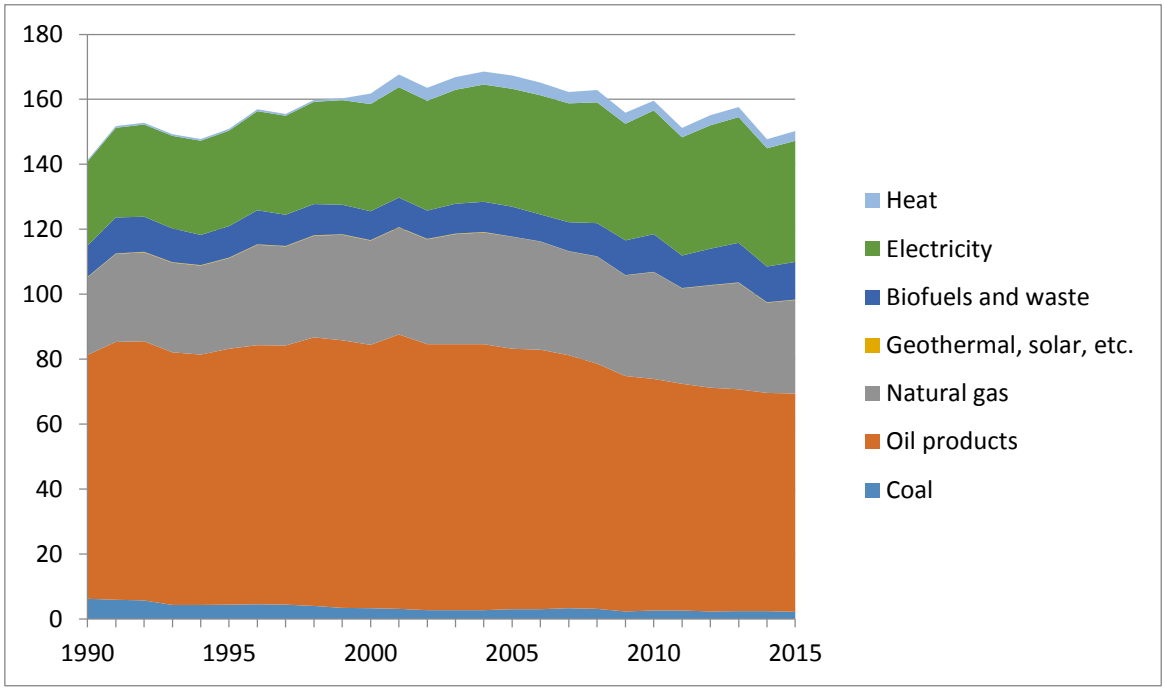


Fig. 21 Total Final Consumption (TFC) by source – France, 1990-2015 (Data source: IEA)

France's 65% of total final energy consumption depends on fossil fuels, where oil and natural gas are the main sources. Oil and natural gas amounted for 67 Mtoe and 29 Mtoe of final energy consumption, respectively in 2015. However, in 1990, oil and gas represented for 75 Mtoe and 24 Mtoe, respectively. This shows that over these years, the share of oil has decreased but at the same time natural gas share has increased in TFC. However, in 2015, oil was still the main energy carrier followed by electricity and natural gas. The share of electricity has increased significantly from 25 Mtoe in 1990 to 38 Mtoe in 2015. Heat and renewables share has also increased over the years. Coal contribution was negligible and contributed just over 2% in France's TFC in 2015.

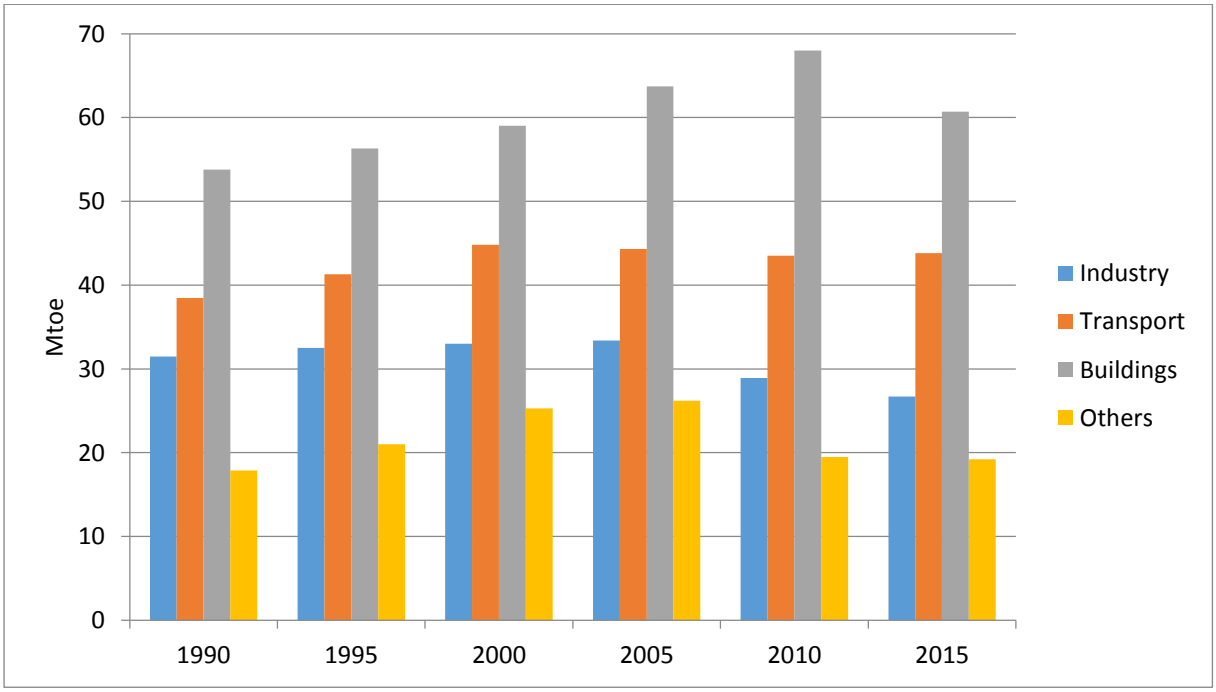


Fig. 22 Total Final Consumption (TFC) by sector – France (Data source: IEA)

Building is the largest energy consuming sector followed by transport and industry. In 2015, the transport and building sector demand has increased whereas industry sector demand has decreased compared to 1990. The transport sector consumption was lowest in 1990, where it accounted for 38.6 Mtoe. The consumption reached the highest level in 2002 that amounted to 45.3 Mtoe, since then transport consumption reduces by 3.4%, amounted to 43.8 Mtoe in 2015. The total share of transport in final consumption represented 29.1% in 2015. Oil was responsible for over 90% of total demand in transport.

The Building sector comprised of residential and commercial sectors, accounting for 55% of TFC in 2015. The demand from the building sector was increasing until 2010. In 1990, the demand was 53.8 Mtoe, which has increased to 60.7 Mtoe in 2015. The building sector demand has reached to the highest level with consumption of 68 Mtoe in 2010, fell by 11% in last 5 years. Since 1990, energy mix of the building sector has also changed. In 1990, electricity and oil were the main sources to meet the building demand, which has changed to electricity and natural gas in 2015. In these years, share of oil has declined, while electricity and natural gas share has increased in the final consumption of building.

The industry sector is the third largest energy consumer, accounting for 17.7% of TFC in 2015. Since 1990, the demand from this sector has declined by 15% and reached the lowest level of 26.7 Mtoe in 2015. Since 2009, after the economic crisis, demand from this sector has declined. The sector relied mainly on oil, natural gas and electricity to meet its demand. .The consumption of oil in the industry sector has also decreased in 2015.

3.2.3 Energy security – security of supply

France net energy imports decreased marginally from 119.2 Mtoe to 116 Mtoe in 2015 compared to 1990. Initially, net energy imports increased gradually from 119.2 Mtoe to 144.6 Mtoe until 2005, and then started to decline to the lowest in 2014. The highest net energy import made between 2000 and 2010. In a last decade, both energy imports and exports have decreased by 17% and 7%, respectively.

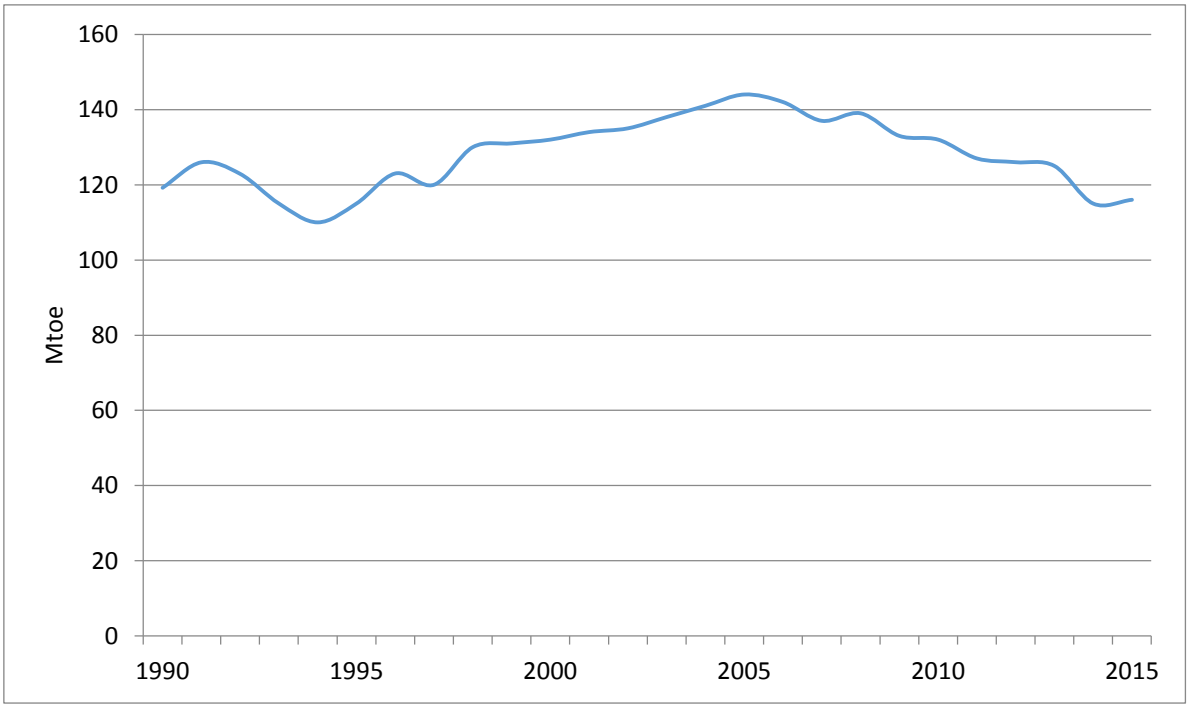


Fig. 23 Net energy imports- France, 1990-2015 (Data source: IEA)

Oil and coal imports decreased over the years, natural gas import increased significantly during the same period. Compared to 1990, oil and coal imports declined from 69.5 Mtoe to 56.7 and 13.4 Mtoe to 8.6 Mtoe, respectively in 2015. In last 10 years, coal import decreased by 38% in 2015. Natural gas import increased significantly from 27.4 Mtoe to 43.7 Mtoe, up by 38% in 2015. Energy exports were reduced in France energy supply over the years. The exports of oil and coal were negligible, however, natural gas exports were increased from negligible 0.33 Mtoe to 5.3 Mtoe in 2015 relative to 1990 (IEA, 2016).

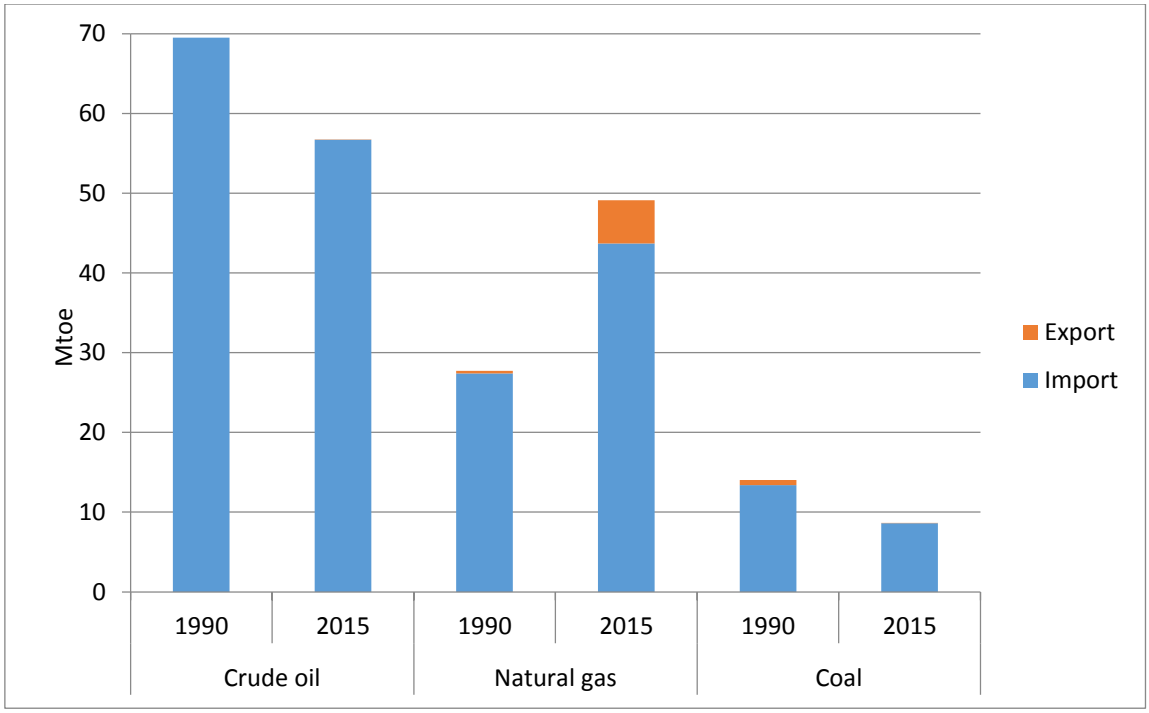


Fig. 24 Energy import-export – France (Data source: IEA)

France is heavily dependent on the import of crude oil because of negligible amount of domestic production. France mostly imported crude oil from the countries like Saudi Arabia, Kazakhstan, Russia and Angola (IEA, 2016). In addition, France also imported oil products from the countries including Russia, USA, Netherlands, Belgium and Germany. France has good infrastructure to import crude oil and oil products. France has three main sea ports from which oil can be imported. All the oil refineries are connected to the port through pipelines. There are three main crude oil pipelines. In 2015, France had total 8 oil refineries, storage capacity amounted for 45.7 million cubic meters (mcm), 60% of which was kept only for oil products (IEA, 2016). .

France is also dependent on import of gas because of the negligible amount of domestic production. France imported gas supply from the countries like Norway, Russia, Netherlands, and Algeria. In all these countries, France imported gas from Norway on a large scale and import of gas from Norway has increased to 88% in the last decade (IEA, 2016). France has good infrastructure for gas with massive pipeline network and LNG terminals. France has four LNG terminals and 15 natural gas storage facilities (IEA, 2016). France also build transport corridor to pass gas from North Sea and North-West Europe to Spain and Italy.

3.2.4 Climate change mitigation - CO2 emissions reduction

France has the lowest CO2 emission in three countries, thanks to nuclear power. The CO2 emission has reduced from 345 Mtoe to 292 Mtoe, fell by 15% in 2015 compared to 1990. Since 1990, for the first time CO2 emissions level reached below 300 MtCO2 in 2014. In 2005, the emissions reached the highest level of 371.8 MtCO2, since then the emissions started to decline and reached the lowest level of 285 MtCo2 in 2014; reduces by 24% in 10 years.

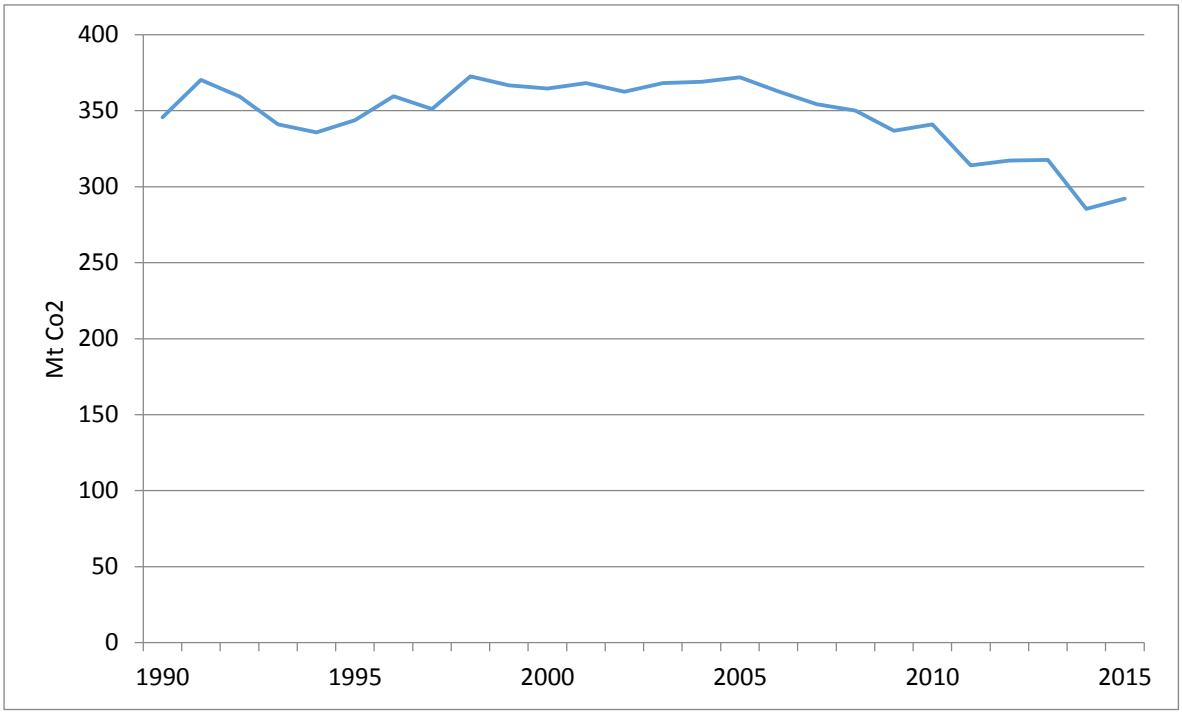


Fig.25 Annual CO2 emissions- France, 1900-2015 (Data source: IEA)

The fig. 25 describes the CO2 emissions by sector from 1990 to 2015. Historically, transport sector is the largest emitter of CO2 emissions among all the sectors. In 1990, transport sector represented for 32% of the total CO2 emissions, which was increased to 42% in 2015. The main reason for this growth is that transport sector relied heavily on fossil fuel, mainly the oil consumption.

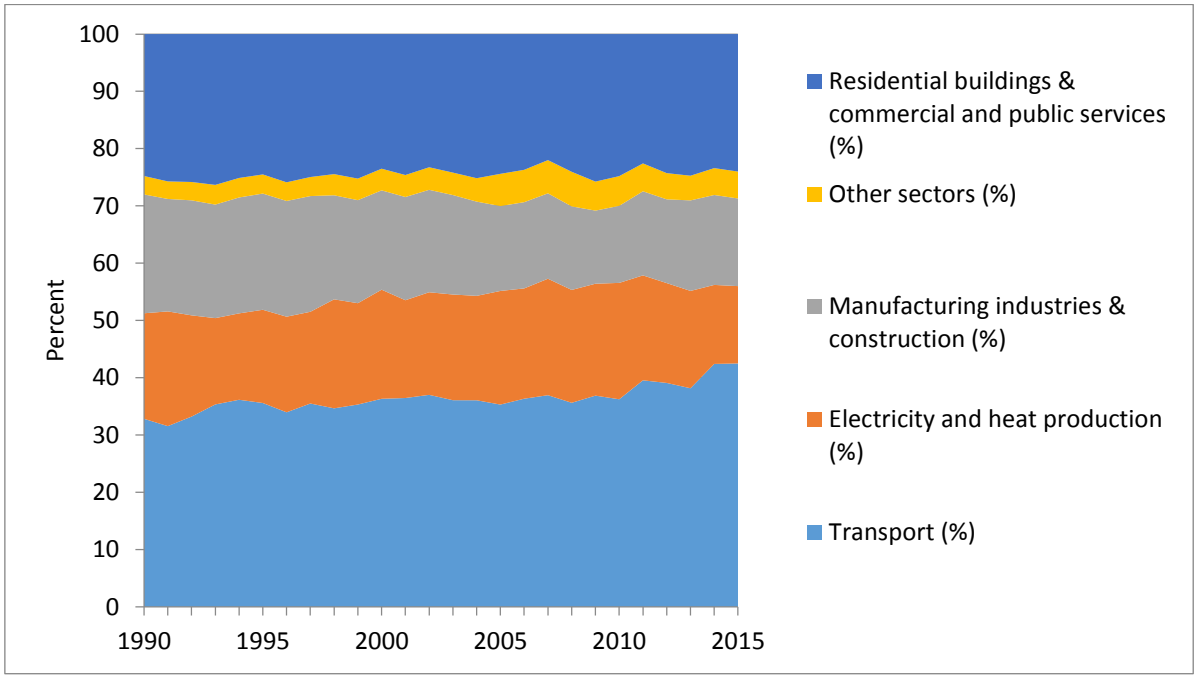


Fig. 26 CO2 emissions by sector- France, 1900-2015 (Data source: IEA)

The building sector is the second largest emitter with a contribution of 24% of the total CO2 emissions. The building sector share in the CO2 emission was stable over the years. This sector was required two pillars of energy transition i.e. energy efficiency and renewable energy for decarbonizing their buildings, which was done by the French government through the establishment of energy transition law, where the building energy efficiency measures are prescribed.

Manufacturing industries and electricity sector represented 15.3% and 13.5% of CO2 emissions, respectively. The share of CO2 emissions from both the sectors has decreased since 1990. The electricity sector represented 18.4% of total CO2 emissions in 1990, which was reduced to 13.5% in 2015, thanks to the contribution of nuclear power. Similarly, the share of CO2 emission from manufacturing industries reduced from 21.7% to 15.3% in 2015 compared to 1990.

3.2.5 Renewables in electricity generation

Electricity is an important final energy carrier for decarbonizing any country's energy system. Electricity can be produced from fossil fuels or renewables, but renewables makes the electricity production more sustainable. A large amount of CO2 emissions can be saved if the electricity generated from the renewable energy sources.

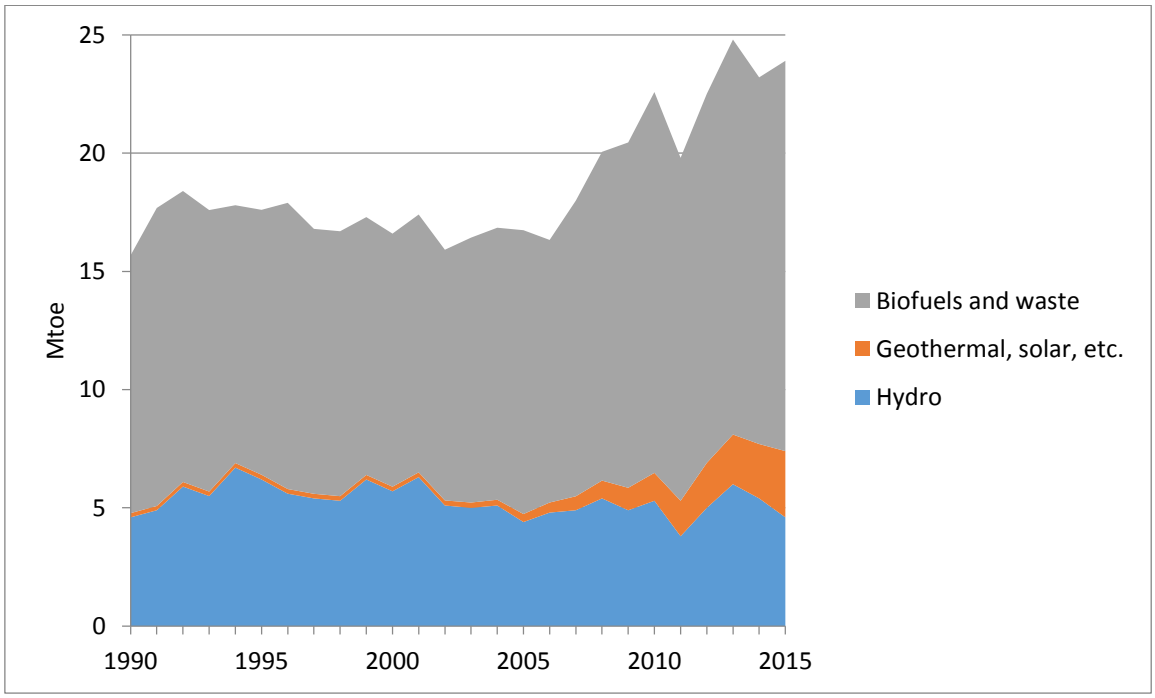


Fig.27 Renewable energy in total primary energy supply – France, 1990-2015 (Data source: IEA)

The share of renewables in the total primary energy supply has increased from 6.7% to 9.5% in 2015. Since 1990, the renewables share has marginally increased from 15.6 Mtoe to 23.9 Mtoe of TPES. Hydro contribution in the TPES was quite stable in the last three decades. Solar has progressed slightly from almost nil to 2.8 Mtoe in 2015 compared to 1990. Biofuels share has also increased from 2% to 6.5% of TPES in 2015 compared to 1990. Biofuels contribution has increased from 10.9 Mtoe to 16.5 Moe in 2015 relative to 1990.

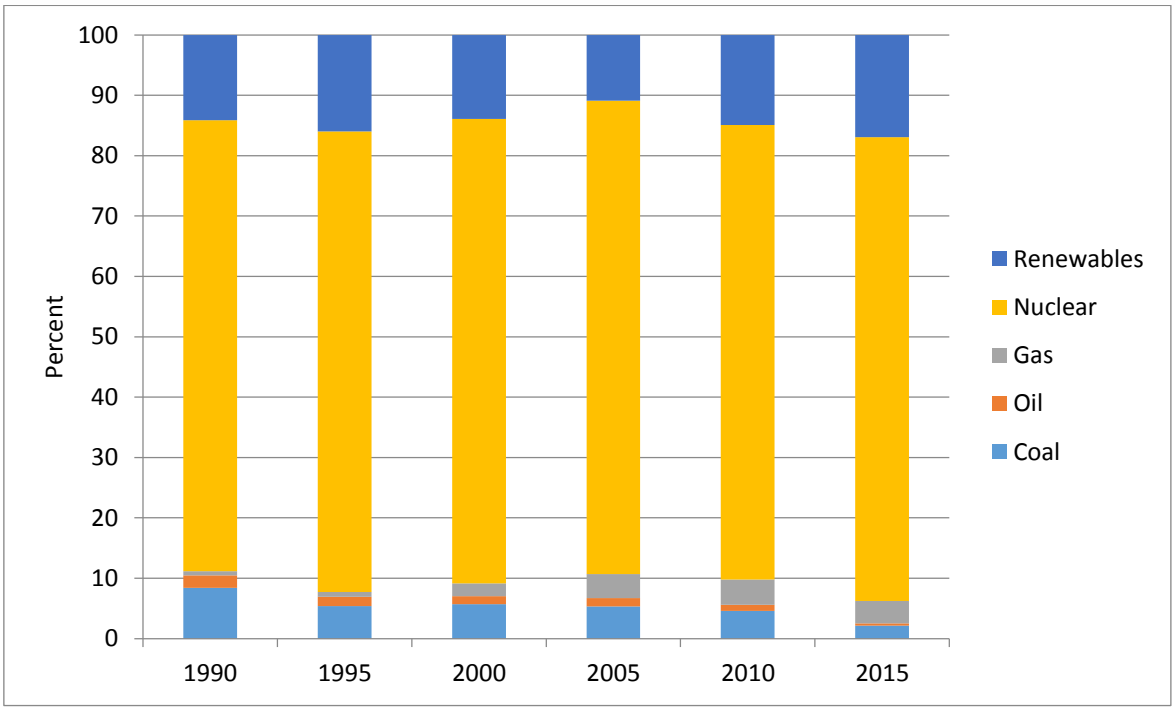


Fig. 28 Electricity generation by fuel – France (Data source: IEA)

The net electricity generation of France totaled to 570 TWh in 2015, grew by 26% from 1990 level of 420 TWh. Historically, France's electricity mix was dominated by nuclear power followed by hydro power. The nuclear share in the electricity mix increased marginal from 74% to 76% in 2015 relative to 1990. The nuclear power amounted to 437 TWh in 2015 compared to 314 TWh in 1990. The renewables share in the electricity mix has also increased from 14% to 17% in 2015 relative to 1990. The share of renewables decreased to 11% in 2005, which went up again in 2015. The renewable power amounted for 60 TWh in 1990, which has increased to 96.6 TWh in 2015.

Fossil fuels including coal (2.2%), oil (0.3%) and gas (3.5%) represented 6.2% of total electricity generation in 2015. In 1990, fossil fuels represented only 11% of electricity generation, where remaining electricity was produced from nuclear and hydropower. Moreover, coal and oil share in the electricity generation has decreased significantly since 1990. Coal consumption has decreased from 8.4% to 2%, whereas oil consumption has decreased from 2% to negligible 0.3% in 2015 compared to 1990. However, natural gas share in the electricity generation has increased from negligible 0.7% to 3.7% in 2015 relative to 1990.

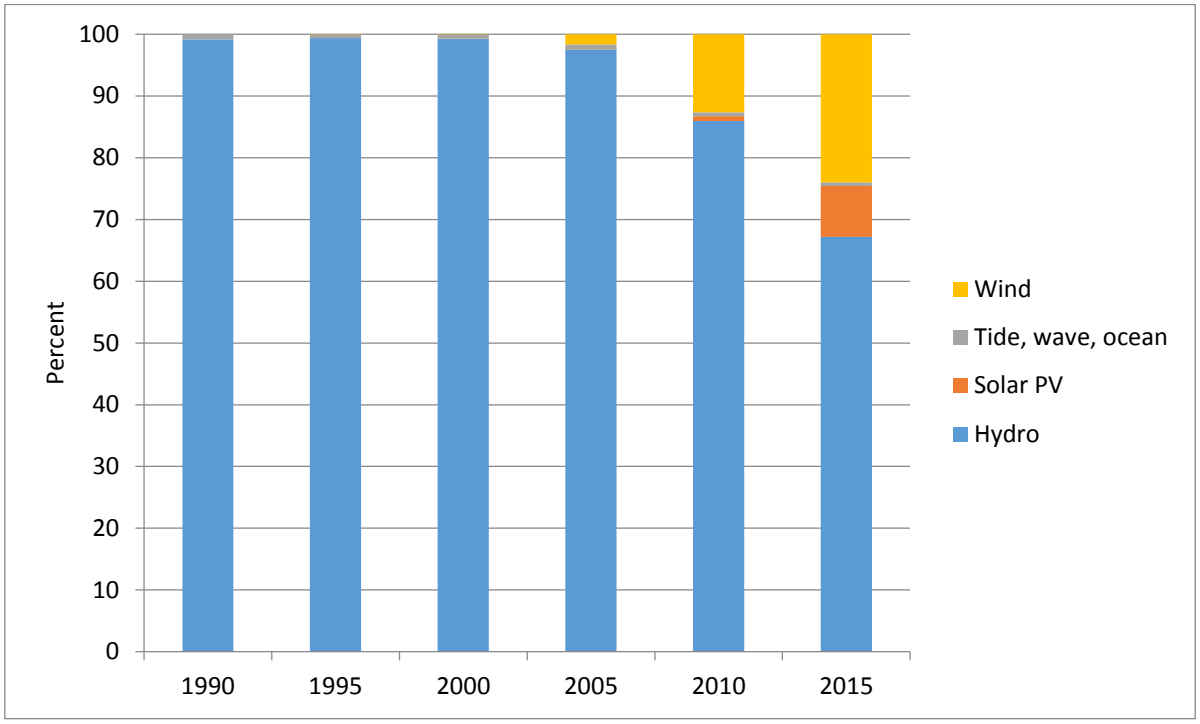


Fig. 29 Electricity generation from renewables by source – France (Data source: IEA)

In 2015, 88.3 TWh of electricity was generated from renewables compared to 58 TWh of electricity in 1990. Hydro is the main source of renewables for an electricity generation in France. Between 1990 and 2000, hydropower made up almost 100% of electricity generation. The share of hydro has decreased from 99.1% to 67.1% in 2015 compared to 1990. In 2005, the hydropower shared decreased slightly but still contributed to 97.4% for electricity generation. For the first time in 2010, the hydropower shared went below 90% and represented 86% of electricity generation. Wind power shared 12.6% of electricity generation and the remaining was shared by solar PV and tide. In 2015, the hydropower share fell to 67.1% and the wind power share increased to 24%. Solar PV share also increased to 8.2% in 2015, which was languishing at 0.78% in 2010. In 2015, 7 TWh of electricity was generated from solar PV. There has been an enormous growth of solar PV share in the electricity generation in the last five years.

3.3 Historical decarbonisation trends of the United Kingdom

This part analysis the historical decarbonisation trends in the UK for the period 1900-2015. The table 6 and fig 30 & 31 compares the main characteristics of the UK's energy sector in 1990 and 2015

Fig. 30 Total Primary energy supply (TPES) – UK (Data source: IEA)

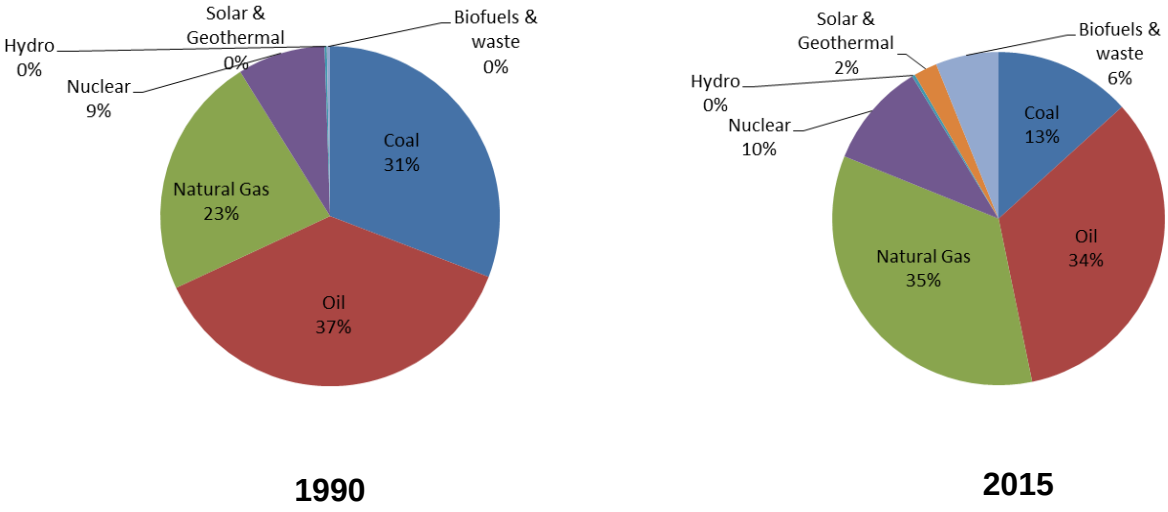


Fig. 31 Total Final Consumption (TFC) – UK (Data source: IEA)

Table 6: Main characteristics of the UK's energy sector (Data source: IEA)

Indicators	1990	2015
Population (millions)	57	65
Total Primary Energy Supply (TPES) (Mtoe)	206	182
Total Final Consumption (TFC) (Mtoe)	138	126
Energy production (Mtoe)	208	118
Net imports (Mtoe)	5	73
CO2 emissions from fuel combustion (MtCO2)	549	393
Renewable electricity generation (TWh)	7	57

3.3.1 Energy supply side

The total primary energy supply (TPES) decreased from 204 Mtoe to 179 Mtoe in 2015 compared to 1990, which was 12.5% declined from the 1990 level. The TPES reached to the highest level in 1996 and 2003, where it amounted to 224 Mtoe, where the TPES reached to the lowest in 2016, where it amounted to 177 Mtoe. The TPES went below 200 Mtoe for the first time in 2009. Since 2010, the total primary energy supply has been gradually decreasing with an average of 0.9% due to the adoption of Climate Change Act.

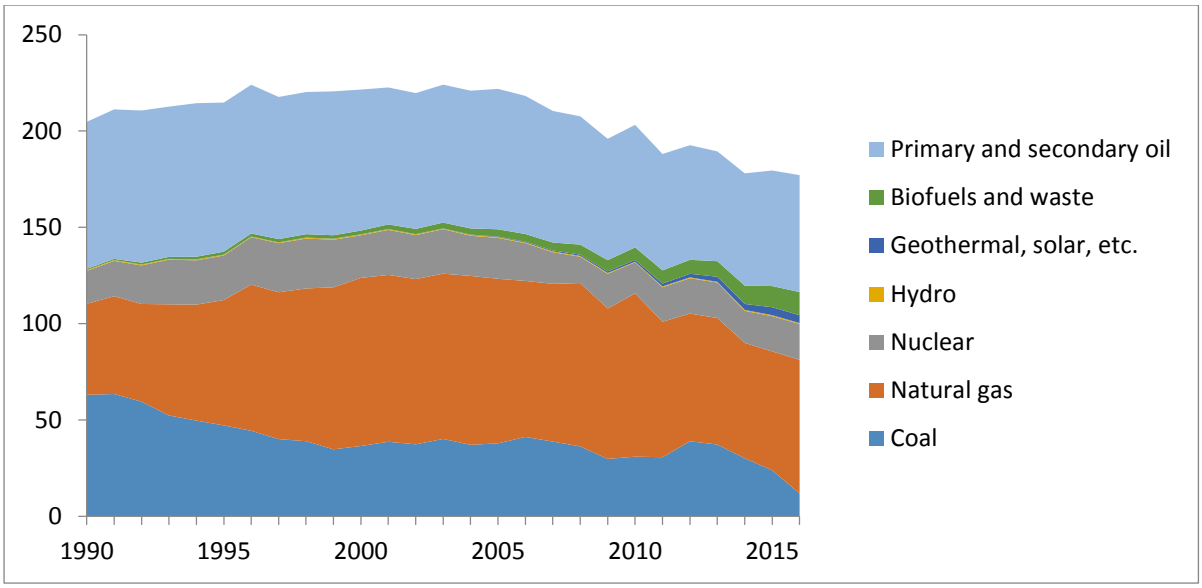


Fig. 32 Total Primary Energy Supply (TPES) by source - UK, 1990-2015 (Data source: IEA)

Historically, coal was the dominant fossil fuel source in the United Kingdom energy supply mix. However, the energy supply mix of UK has changed significantly in 2015 compared to 1990. In 1990, coal and oil was dominating the energy supply mix of UK, where it accounted for 30% and 37% of TPES, respectively. Nuclear gas was the third largest energy source that amounted to 47.2 Mtoe, representing 23% of TPES in 1990. However, natural gas surpassed the coal and oil of total primary energy supply in 1995 and 2000, respectively. Oil supply has slowly declined in the energy supply mix since 1990. The notable change has been seen in the coal supply. Coal was dominating the UK's energy supply mix in 1990 with 30.8% of TPES, but it declined drastically in 2016, representing 6.6 % of TPES. In actual, coal was gradually decreasing from 1990 but the UK government Climate Change Act made the major impact towards its rapid downfall.

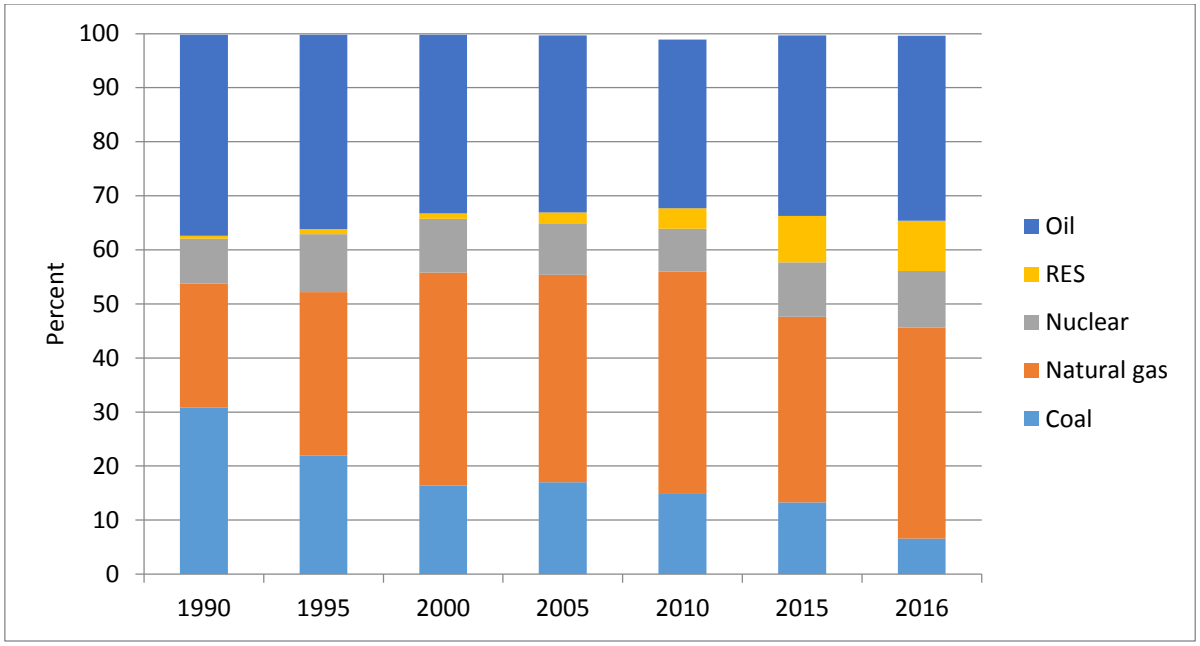


Fig. 33 Fuel shares in primary energy, UK (Data source: IEA)

The Climate Change Act has made a huge impact in the energy supply mix while increasing the share of clean energy. A big change was seen in the share of renewable energy sources in 2015 when it has increased from 0.5% to 9% compared to 1990. The RES supply has increased from 1 Mtoe to 15.6 Mtoe in 2015 compared to 1990. The nuclear energy share has also increased from 8% to 10% in 2015 relative to 1990. In 1990, the nuclear energy amounted to 17 Mtoe of TPES, which has increased to 18.3 Mtoe in 2015. Initially, the nuclear energy supply has increased until 2005, reaching the highest in 1998 where it amounted to 26 Mtoe. The nuclear supply downfall started in 2006 and reached the lowest in 2008, where it was amounted to13.6 Mtoe. The next year in 2009 the nuclear energy supply has increased to 18 Mtoe, since then it was fluctuating between 16 Mtoe and 18 Mtoe.

3.3.2 Energy demand side

The total final consumption (TFC) in the United Kingdom has declined from 137 Mtoe to 125 Mtoe in 2015, fell 8.5% relative to 1990. From 1990 to 2001, the TFC was gradually increasing as country's economy was also growing during this period. The TFC reached the highest in 1996, where it amounted to 151 Mtoe. Since 2004, TFC has been gradually decreasing and reached the lowest level in 2014, where it amounted to 122.7 Mtoe.

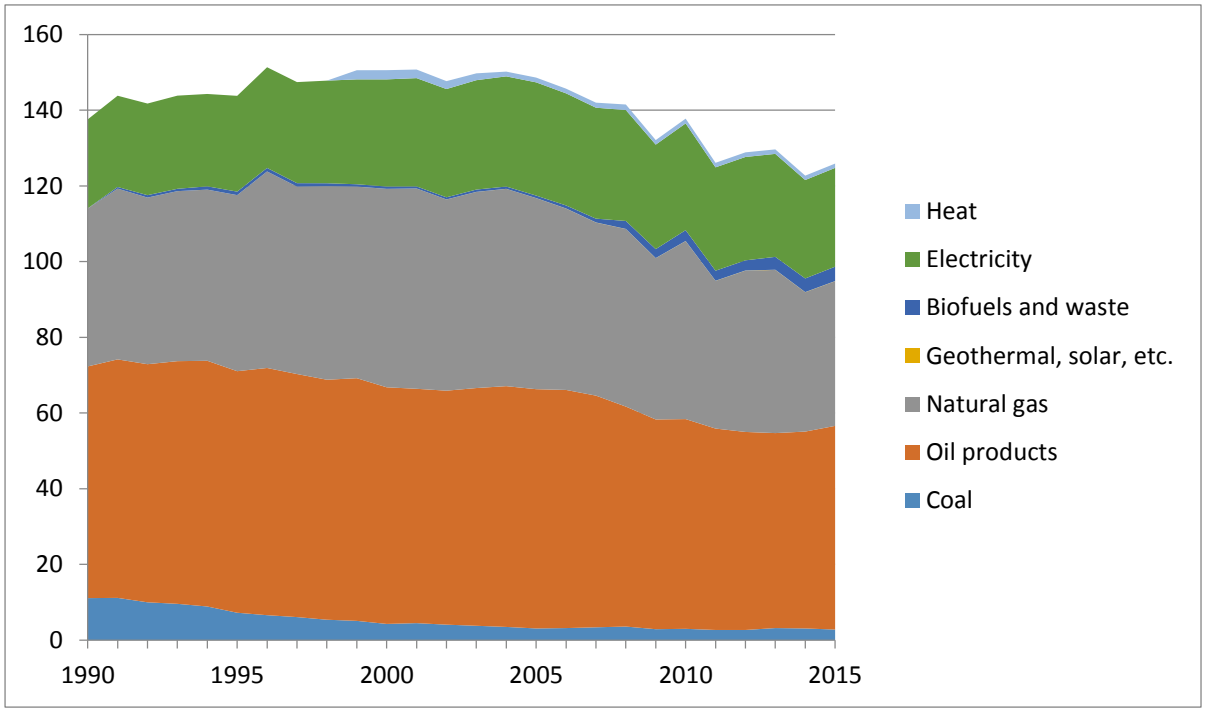


Fig. 34 Total Final Consumption (TFC) by source - UK, 1990-2015 (Data source: IEA)

Historically, final energy consumption in the UK is heavily dependent on fossil fuels due to the extensive use of oil and natural gas. The oil and gas consumption has been declining over the years but still contributed the highest shares of TFC. The oil represents the largest energy carrier followed by natural gas and electricity. The natural gas consumption decreased from 42 Mtoe to 38 Mtoe in 2015 compared to 1990. The gas consumption reached the highest level in 2001, where it amounted to 53 Mtoe. Between 1996 and 2005, the gas consumed over 50 Mtoe, since then it has started to decline and reached the lowest level in 2014, where it amounted to 37 Mtoe. The coal demand has significantly reduced from 11 Mtoe to 2.8 Mtoe in 2015 compared to 1990, representing 2% of TFC. The final energy demand for electricity and renewables has increased over the years. The electricity consumption has increased from 17% to 21% of TFC in 2015 compared to 1990.

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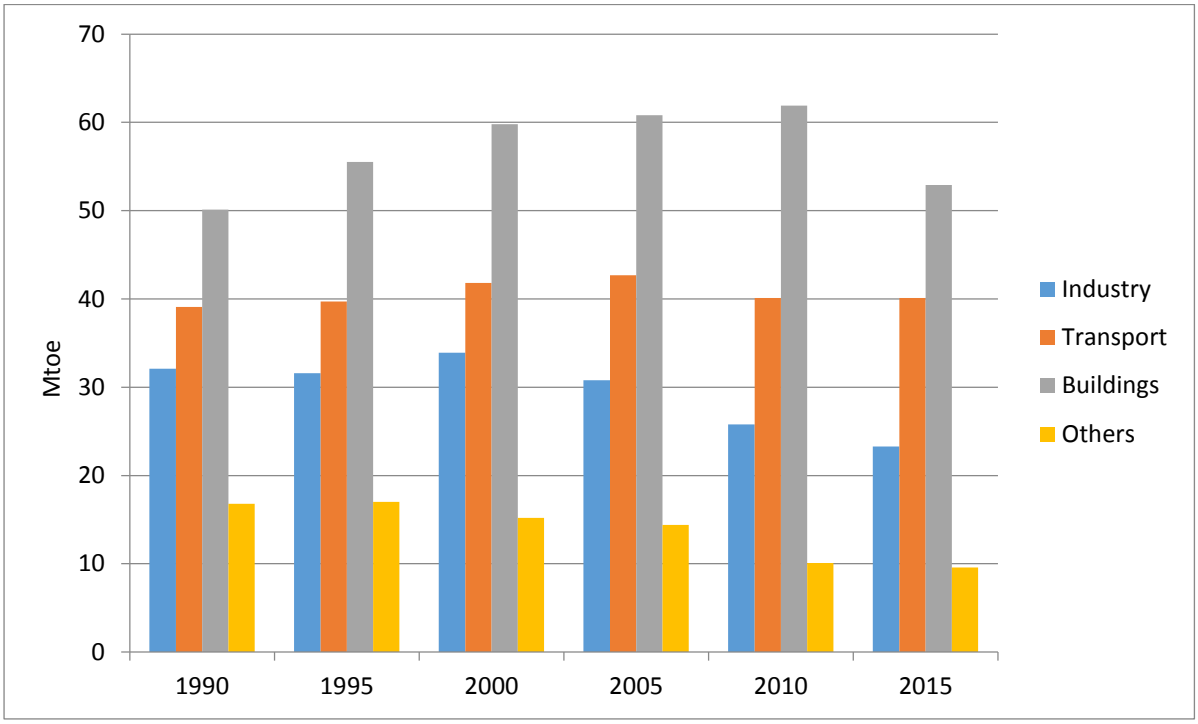

Fig. 35 Total Final Consumption (TFC) by sector – UK (Data source: IEA)

The buildings are the largest energy consuming sector followed by transport and industry in the UK. The building sector and transport sector jointly consumed 42% of total final energy consumption in 2015. The building sector energy consumption has increased from 50 Mtoe to 53 Mtoe in 2015 compared to 1990 level. The consumption has increased gradually until 2010, where it reached the highest 62 Mtoe. Since then the final energy consumption of building has declined drastically.

The transport sector consumption hasn't changed much over the years. This is because UK has good transport policy in which they encourage people to use more public transport. In 1990, the sector consumption amounted to 39 Mtoe, and in 2015 the consumption has marginally increased to 40 Mtoe. The transport sector consumption reached highest in 2005 where it amounted to 42.7 Mtoe. The industry sector consumption has decreased from 32 Mtoe to 23 Mtoe in 2015 compared to 1990. The industry sector share also decreased in the total final energy consumption. The share of industry sector has decreased from 23% to 18% of TFC in 2015 compared to 1990.

3.3.3 Energy security- security of supply

The United Kingdom has increased its import dependency to eight-fold in 2015 compared to 1990. The dependence on import has increased significantly from 4.73 Mtoe to 72.63 Mtoe in 2015, which raises the concern for UK's energy security issue. However, no energy was imported during a period from 1993-2003. This is because at this time, the domestic energy production was much higher than the consumption, due to which the energy was also exported. Since 2004, there has been a huge increase in the energy imports, particularly of oil and gas. Even, the net energy import has reached the highest level of 96 Mtoe in 2013. However, it has decreased by 25% over the next two years.

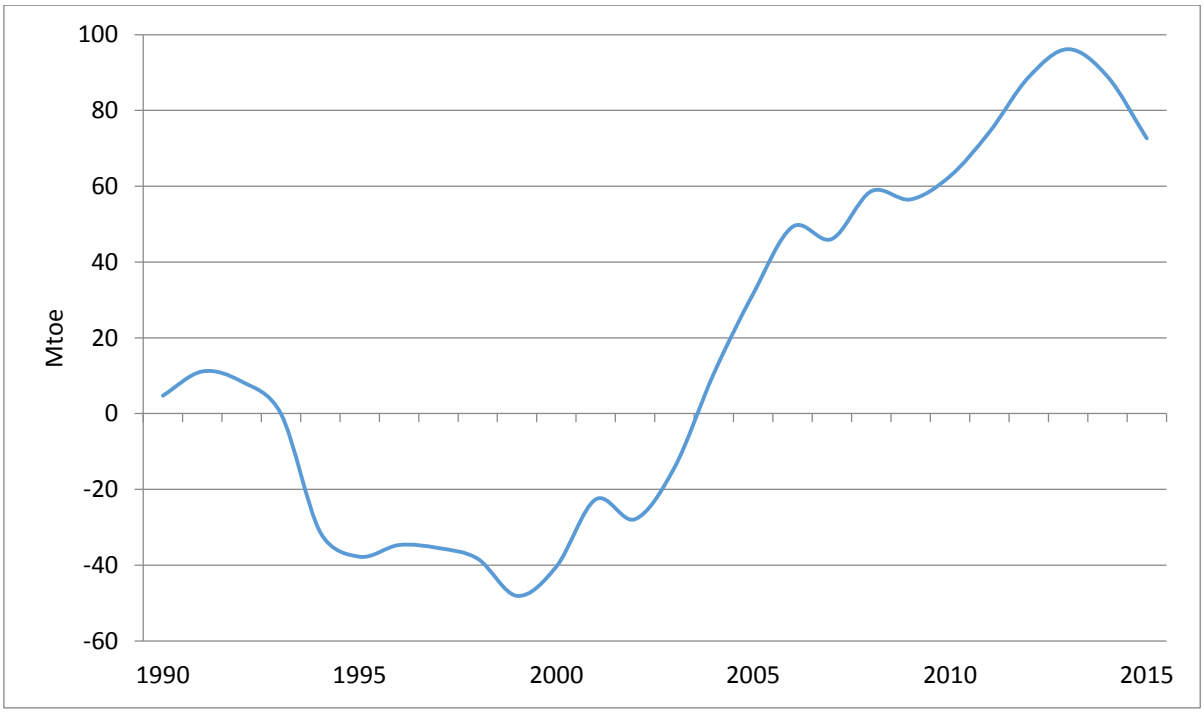

Fig. 36 Net energy imports - UK, 1990-2015 (Data source: IEA)

The growth of oil import has been steady since 1990 but at the same time exports of oil has decreased to 45%. Net natural gas import dependence has increased over the years. Although the natural gas import has significantly increased from 6 Mtoe to 42.5 Mtoe in 2015 relative to 1990, export of gas has also increased from zero to 13 Mtoe in 2015. The United Kingdom exports most of its gas to continental Europe and Ireland (IEA 2016). The UK is also dependent on coal imports to meet its needs. In

2015, the UK imported almost all coal, where the coal import has increased from 10 Mtoe to 15 Mtoe in 2015 compared to 1990, However, the import of coal has reached the lowest in 2016, which amounted to 6.3 Mtoe (IEA 2016).

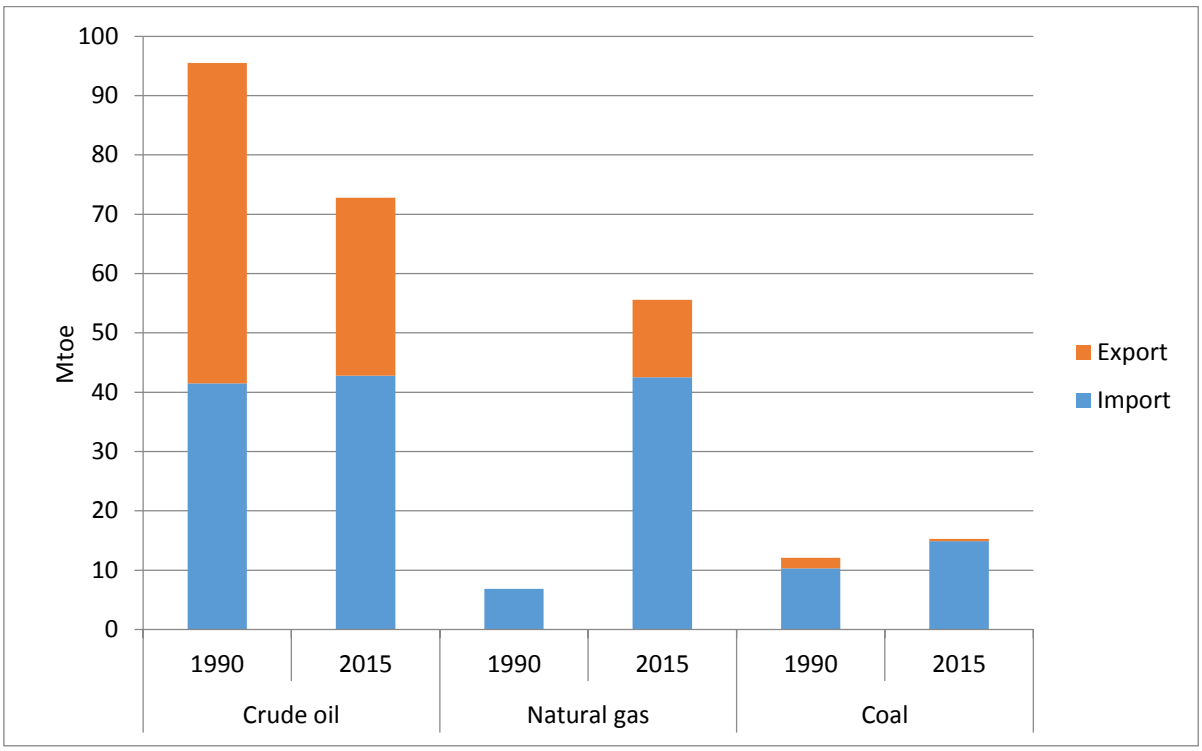

Fig.37 Energy import-export – UK (Data source: IEA)

The UK has also increased the import infrastructure due to increasing dependence on imports. For example, the infrastructure of gas pipeline and import terminals has increased between 2005 and 2015. The UK gas pipelines mainly connected to the Norwegian North Sea fields and Continental Europe for the cross border connections. Storage is also important infrastructure that provides flexibility. The UK has three types of storage – Long range, medium range and short range storage for seasonal and daily variations usage (IEA, 2012).

3.3.4 Climate change mitigation - CO2 emissions reduction

The United Kingdom has made a serious effort to reduce its CO2 emissions. Since 1990 the CO2 emissions have gradually and reached 29% below 1990 levels in 2015. For the first time the emission level has reached below 400 MtCO2 in 2015. The decrease in emissions was driven by switching to less carbon intensive fuels

particularly, from coal-fired power generation to natural gas power generation. Additionally, reductions in energy-intensive industry output and increase in efficiency, particularly in building and transport also contributed in reducing the emissions.

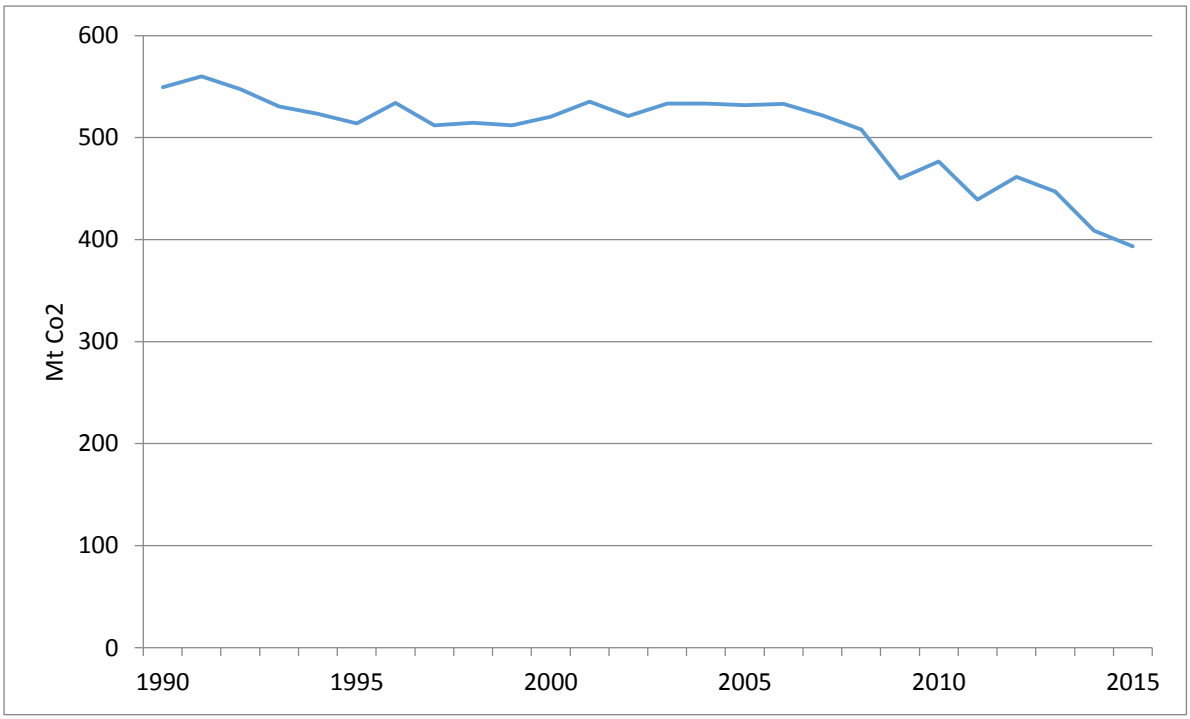

Fig.38 Annual CO2 emissions - UK, 1990-2015 (Data source: IEA)

It was seen that from 1990 to 2008, the CO2 emissions have fallen gradually despite the increase in energy consumption and economic output. This was mainly due to switching on low carbon-intensive fuel. Coal and oil have high emission factors than natural gas. During this period, the consumption of coal and oil has decreased, whilst the share of natural gas has increased (IEA, 2016). In 2009, due to the global economic crisis, CO2 emissions fell significantly from 508 MtCO2 to 460 MtCO2, 9.5% fall relative to 1990. In 2010, economic activity has improved due to which the emissions increased again. However, since then, the emissions level is declining and reached the lowest in 2015, which amounted to 393 MtCO2. This is because the UK government established the Climate Change Act in 2010 which resulted in a sharp reduction in CO2 emissions.

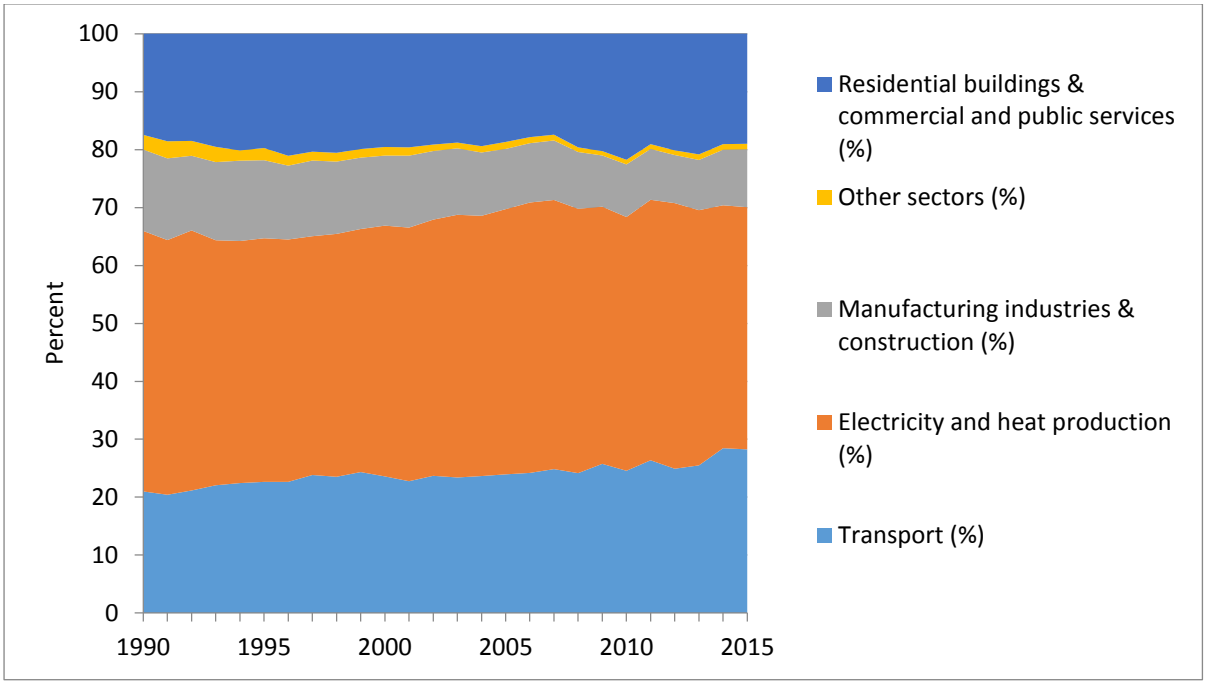

Fig. 39 CO2 emissions by sector - UK, 1990-2015 (Data source: IEA)

The fig. 39 illustrates CO2 emissions by sector from 1990 to 2015. CO2 emissions accounted for 28% from transport, 42% from electricity and heat production,10% from manufacturing industries & construction, and 19% from buildings of the total CO2 emissions in 2015. The electricity and heat production sector was the largest source of CO2 emissions followed by transport, buildings and industry. The shares of electricity and industry sector CO2 emissions have decreased; whilst the shares of transport and buildings sector CO2 emissions have increased.

Coal was responsible for CO2 emissions in the electricity sector. Coal has high CO2 emission factor and was used for electricity and heat generation in the UK. However, since 2012, coal electricity generation has declined and replaced by natural gas and renewables. Transport sector is also the largest source of CO2 emissions. Oil was responsible for CO2 emissions from transport sector. The UK is highly dependent on oil to meet the transport needs, which resulted in increase of share of CO2 emissions from 21% to 28% in 2015 relative to 1990. The building sector accounted for 17% of CO2 emissions, which increased to 19% in 2015 compared to 1990. The industry sector reduces the CO2 emissions share from 14% to 10% in 2015 compared to 1990.

3.3.5 Renewables in electricity generation

The renewable energy share in the TPES has increased from 0.5% to 9.3% in 2015 compared to 1990. The RES contribution in the primary energy supply has increased from 1 Mtoe to 15.6 Mtoe in 2015 relative to 1990. Biofuels is the largest renewable energy sources that accounted for 74% RES in 2015. Biofuels contribution in the energy supply has increased from 0.6 Mtoe to 11 Mtoe in 2015, representing 6.1% of TPES. Solar energy supply has also increased from almost zero to 4 Mtoe in 2015 relative to 1990, accounted for 25% of RES. The other renewable sources including wind energy and hydro contribution were negligible.

The UK's total electricity generation by fuel from 1990 is presented in Fig. 41. The total electricity generation has increased from 319 TWh to 339 TWh in 2015 compared to 1990. In 1990, the UK's electricity mix was dominated by the coal followed by nuclear and oil, where gas and renewable contribution was negligible. This electricity mix has significantly changed in 2015, where natural gas is the largest energy source followed by renewables, coal and nuclear in 2015.

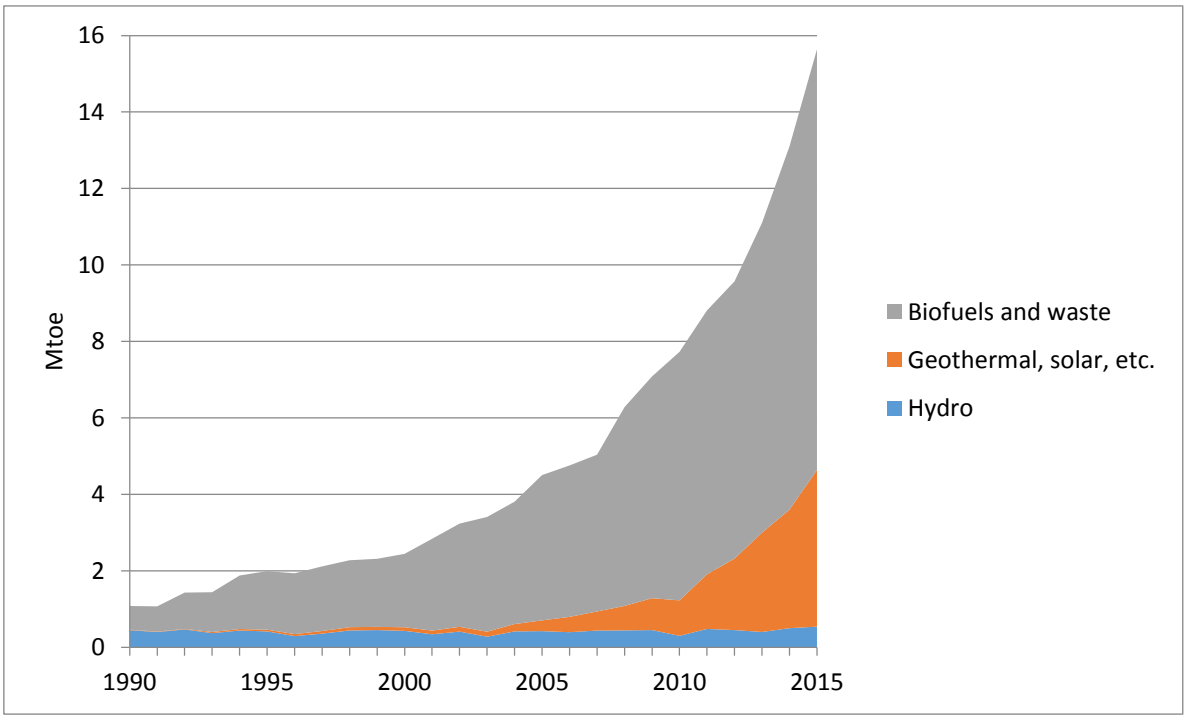

Fig.40 Renewable energy in total primary energy supply - UK, 1990 to 2015 (Data source: IEA)

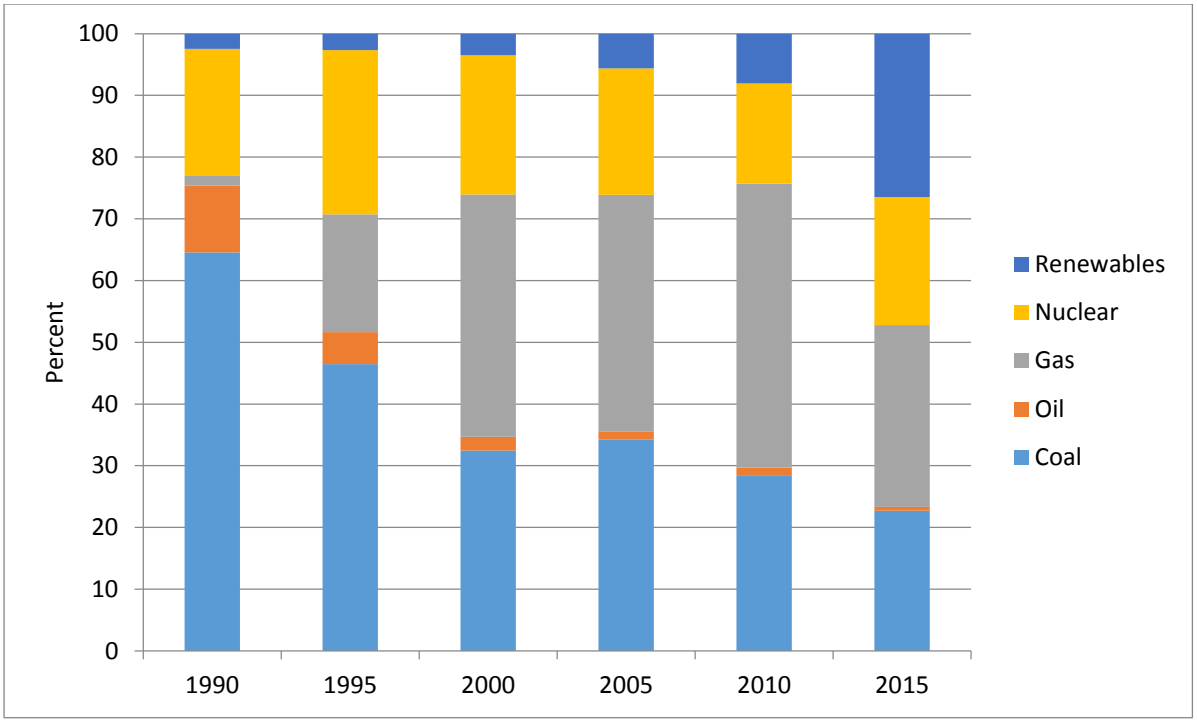

Fig.41 Electricity generation by fuel – UK (Data source: IEA)

The share of renewable energy in total electricity generation has increased from 2.4% to 26.4% in 2015 compared to 1990. In 1990, only 7.9 TWh of electricity produced from renewables that has increased to 90 TWh in 2015. The share of nuclear power in the electricity generation was quite stable in 1990 and 2015, representing 20% of total electricity generation. The nuclear power has slightly increased from 65 TWh to 70 TWh in 2015 compared to 1990. However, the nuclear power reached the highest level in 1995, where it amounted to 89 TWh. From 2005 to 2010, nuclear power decreased drastically from 82 Mtoe to 62 Mtoe, however, it increased again where it amounted to 70 Mtoe in 2015.

Coal was the main source of electricity generation in 1990, where it represented 65% of total electricity generation and generated 206 TWh of electricity. Since then, coal contribution has declined, representing only 22% of total electricity generation in 2015, where it amounted to 77 TWh of electricity. Natural gas share in the electricity mix has increased significantly form 1.5% to 29% in 2015 compared to 1990. Due to low CO2 emission factor and sufficient gas reserves, the UK government decided to increase the share of natural gas in the electricity mix. As a result, electricity generation from natural gas has increased from 5 TWh to 100 TWh in 2015 compared to 1990. Simultaneously, the oil contribution has decreased from 34 TWh

to 2 TWh in 2015 relative to 1990. Oil represents only 0.6% of total electricity generation in 2015.

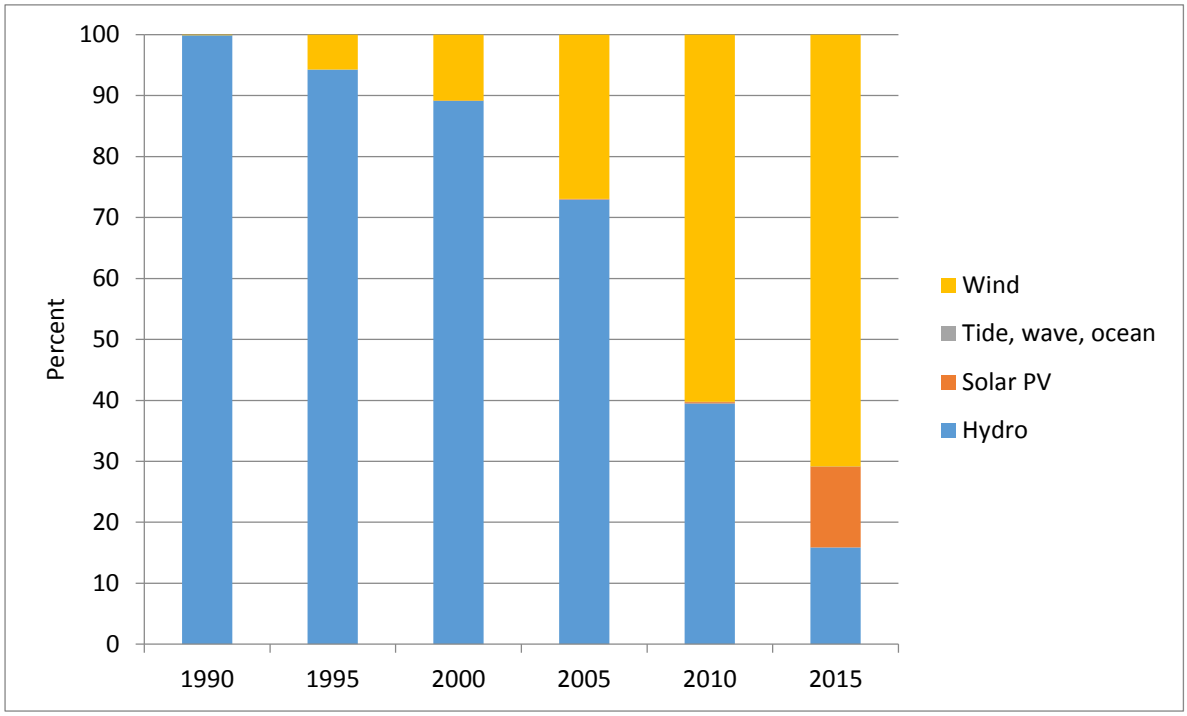

Fig. 42 Electricity generation from renewables by source – UK (Data source: IEA)

In 2015, 90 TWh of electricity generated from the renewable sources compared to 7.9 TWh of electricity in 1990. Hydro made the largest contribution to electricity generation in 1990. From 1990 to 2000, hydro produced more than 90% of electricity, in 1990, about 100% of the electricity was produced from hydro. However, in 2015, the share of hydro falls to 15% of total electricity generation, where 9 TWh of electricity produced. In 2015, wind made the largest contribution to the electricity generation followed by hydro and solar. The share of wind has increased from negligible to 70% in 2015, where it generated 40 TWh of electricity. The solar PV share has also increased from zero to 13%, where 7.5 TWh of electricity generated in 2015.

3.4 Comparative analysis of historical decarbonisaton trends of Germany, France and the UK

This part compares and analysis the historical decarbonisation trends in Germany, France and the UK between 1900-2015. The table 6 compares and summarizes the main characteristics of country's energy sector in 2015.

Table 7: Main characteristics of country's energy sector, 2015 (Data source: IEA)

Indicators	Germany	France	United Kingdom
Population (millions)	82	67	65
Total Primary Energy Supply (TPES) (Mtoe)	308	249	182
Total Final Consumption (TFC) (Mtoe)	220	150	126
Energy production (Mtoe)	120	139	118
Net imports (Mtoe)	198	117	73
CO2 emissions from fuel combustion (MtCO2)	730	292	393
Renewable electricity generation (TWh)	143	88	57

3.4.1 Energy supply side

Germany dominated the total primary energy supply followed by France and the UK. The total primary energy supply of Germany and the UK has decreased while France's total energy supply has increased in 2015 relative to 1990. Germany and the UK's total energy supply decreased by 12% while France's TPES increased by 10% in two and a half decades.

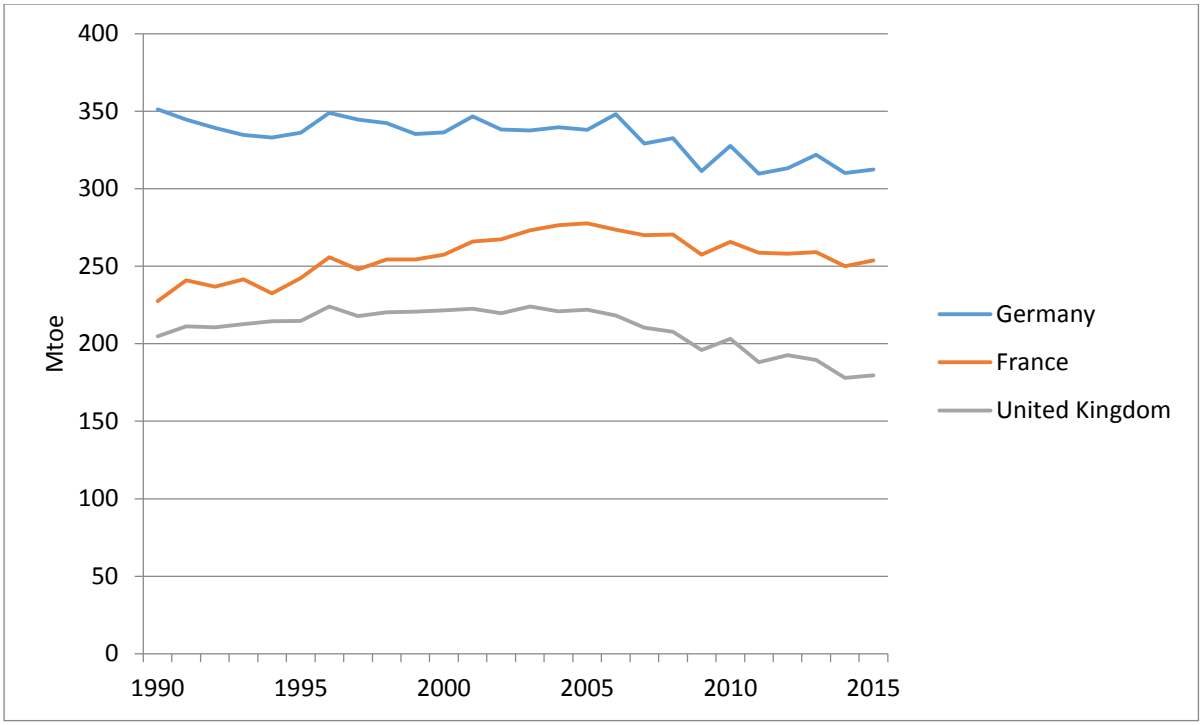

Fig. 43 Total Primary Energy Supply (TPES) by source, 1990-2015 (Data source: IEA)

In 2015, Germany's TPES reached just above 300 Mtoe, where France and the UK energy supply reached 253 Mtoe and 180 Mtoe, respectively. Germany reduced its total energy supply from 351 Mtoe to 312 Mtoe in 2015 compared to 1990, representing 12% decrease in two and half decades. The UK decreased the TPES from 204 Mtoe to 180 Mtoe in 2015 relative to 1990, representing 12% decrease in a quarter years. France increased its total energy supply from 227 Mtoe to 253 Mtoe in 2015 relative to 1990, representing 10% increase in 25 years.

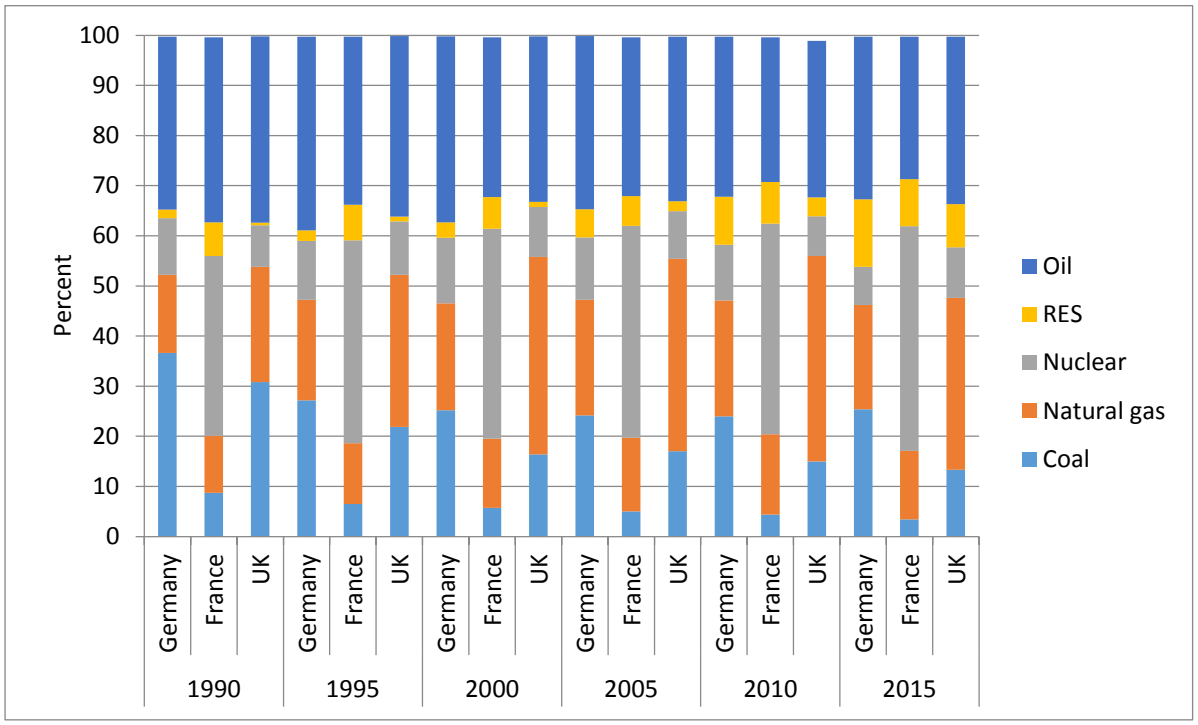

Fig. 44 Fuel shares in primary energy, 1990-2015 (Data source: IEA)

Oil is the largest energy source in total primary energy supply for Germany and the UK while nuclear is the largest energy source for France. Oil accounted for 32% and 33% of TPES for Germany and the UK, respectively in 2015. Nuclear represented for 7.5% and 10% of TPES for Germany and the UK, respectively. France has a nuclear share of 45% of TPES in 2015. Oil is the second largest energy source that accounted for 28% of TPES in 2015. Coal still has a high contribution in the energy supply mix of Germany, where it has contributed 25% of total energy supply. On the contrary, coal has a less contribution in the TPES of France and the UK. France and the UK accounted for 3.5% and 13% of TPES, respectively in 2015. The share of coal has dropped to 6.5% of TPES in the UK in 2016 (IEA, 2016). Natural gas is the second largest energy source in TPES for Germany and the UK. Germany has a natural gas share of 21% of TPES while the UK has a share of 32.8% of TPES in 2015. France has a share of 14% of TPES in 2015. Germany has the highest share of renewables in the total energy supply in 2015. Germany accounted for 13.5% of TPES, whilst France and the UK accounted for 9.5% and 8.5% of TPES, respectively.

3.4.2 Energy demand side

The final energy consumption of Germany and the UK has decreased whereas France final consumption has increased from 1990 to 2015. However, France's TFC has been declining from 2004 after reaching the highest level of TFC. Germany reduced its consumption from 240 Mtoe to 220 Mtoe in 2015 relative to 1990, representing 8.5% decline of TFC. The UK reduced the final consumption from 137.5 Mtoe to 126 mtoe in 2015 compared to 1990, representing 8.5% decline of total final consumption. France increased its consumption form 141 Mtoe to 150 Mtoe in 2015 compared to 1990, representing 6% increase of TFC.

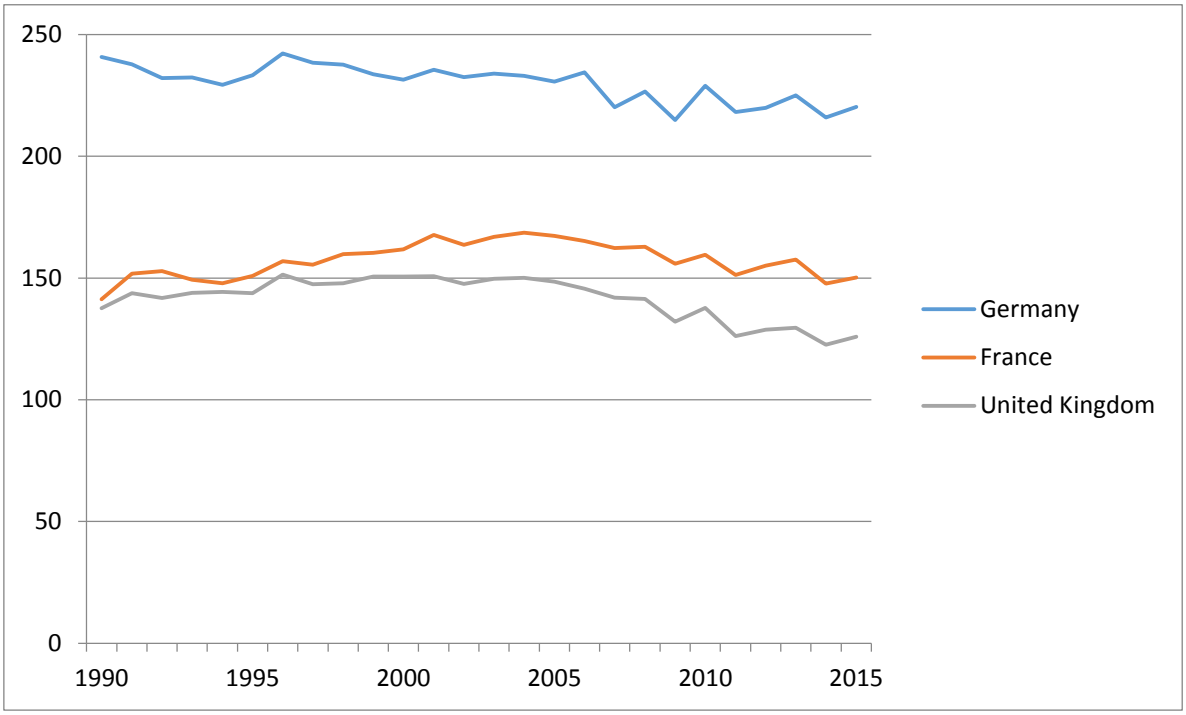

Fig. 45 Total Final Consumption (TFC), 1990-2015 (Data source: IEA)

The buildings are the largest energy consuming sector followed by transport and industry in Germany, France and the UK. The building sector accounted for 40% of total final energy consumption in 2015. Germany's final energy consumption has decreased whilst France and the UK consumption has increased in 2015 compared to 1990. Germany has reduced its final consumption from 92 Mtoe to 87 Mtoe in 2015 compared to 1990, representing 5.5% decrease in 2015. France and the UK increased its building demand from 54 Mtoe and 50 Mtoe, respectively to 60 Mtoe

and 53 Mtoe, respectively in 2015 compared to 1990. It represented for 10% and 6% increase, respectively in 2015 compared to 1990.

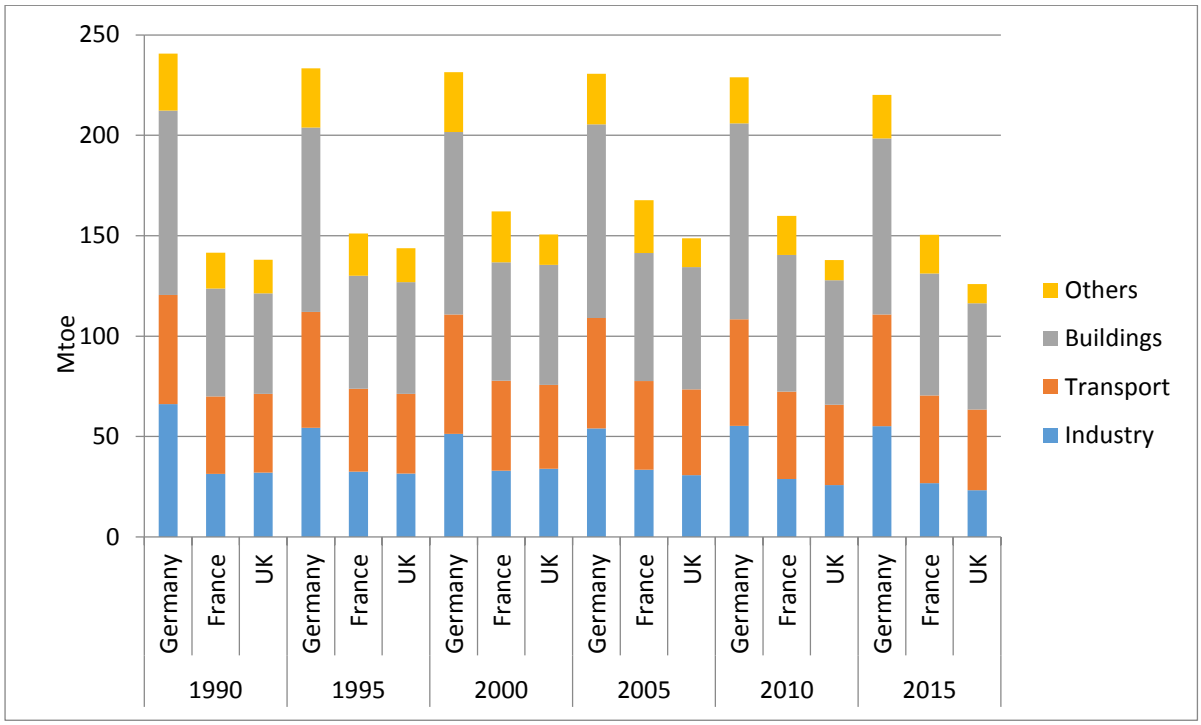

Fig. 46 Total Final Consumption (TFC) by sector, 1990-2015 (Data source: IEA

The transport sector is the second largest energy consumption sector in these three countries. In all three countries, the transport demand has increased in 2015 compared to 1990. In 2015, the transport sector accounted for 25% of TFC in Germany, whilst France and the UK has 29% and 31% share of total final energy consumption, respectively. Germany's transport sector demand has increased from 54.4 Mtoe to 55.6 Mtoe in 2015 compared to 1990. France has increased its transport demand from 38.4 to 43.8 Mtoe, whilst the UK has increased the transport demand from 39 Mtoe to 40 Mtoe in 2015 relative to 1990.

The industry sector is the lowest energy consuming sector in all three countries. The industry demand has decreased in Germany, France and the UK from 1990 to 2015. Germany accounted for 55% of TFC while France and the UK accounted for 26.7 and 23.3% of TFC, respectively in 2015. The UK has decreased the 28% of industry consumption while Germany and France has reduced the industry consumption by 16% and 15%, respectively in 2015 compared to 1990. Germany has decreased its industry consumption from 66 Mtoe to 55 Mtoe in 2015 relative to 1990. France's

industry consumption has decreased from 31.4 Mtoe to 26.7 Mtoe whereas UK's industry consumption has reduced from 32 Mtoe to 23 Mtoe in 2015 compared to 1990.

3.4.3 Energy security – Security of supply

Energy security of a country can be determined through its import dependence. All three countries are dependent on fossil fuel imports to meet their energy demand. From 1990 to 2015, the import dependence of Germany and the UK import has increased whilst France's import dependence has decreased. Germany's net energy import has increased from 167 Mtoe to 198 Mtoe while the UK's net energy import has increased eight-fold from 4 Mtoe to 72 Mtoe in 2015 compared to 1990. In 2015, Germany has increased its import dependence to 16% whilst the UK's import dependence has increased by 94%. However, between 1995 and 2000, the UK exported high quantities of energy, due to which net energy imports became negative. France reduced its net energy imports from 119 mtoe to 117 Mtoe in 2015 compared to 1990, representing 2% decline of import dependence. Until 2005, net energy imports had increased in Germany and France; however, there has been an increase of exports since then, resulting in a decline in net energy imports in 2015.

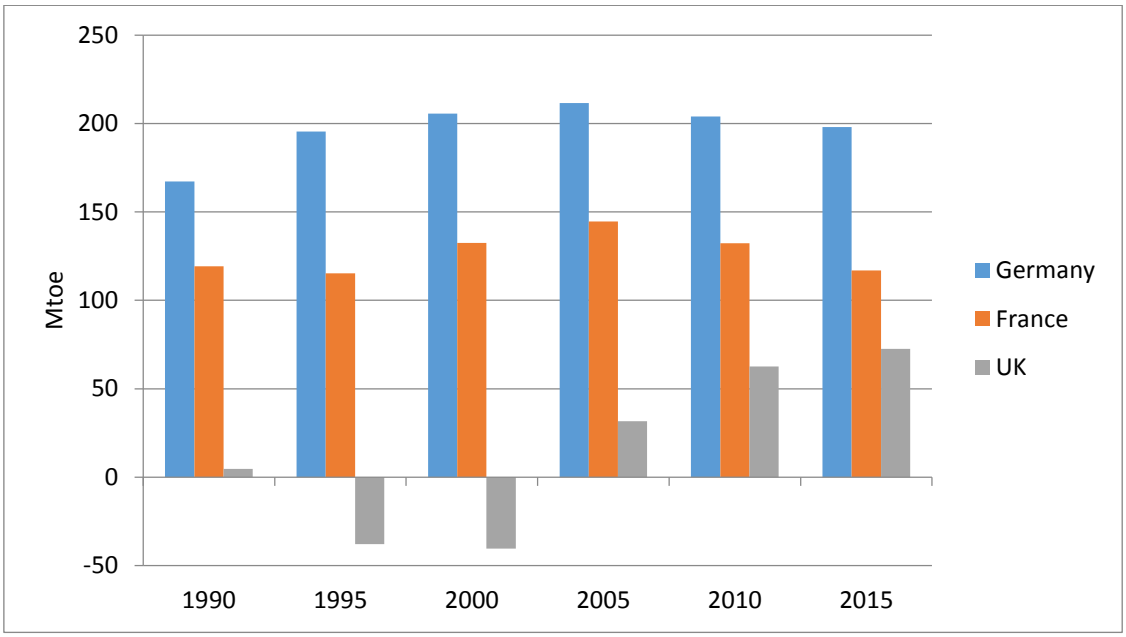

Fig 47.Net energy imports, 1990-2015 (Data source: IEA)

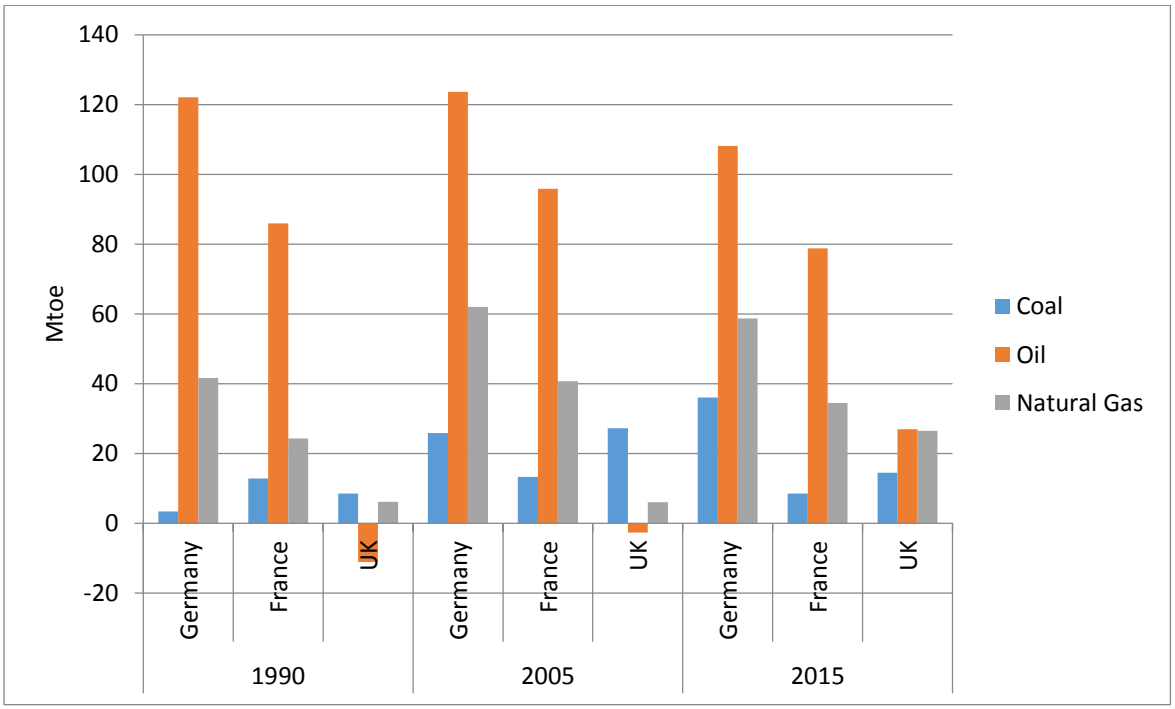

Fig.48 Net energy imports by source, 1990-2015 (Data source: IEA)

Germany, France and the UK are dependent on import of fossil fuels to meet their energy demand. Net coal import has increased in Germany and the UK whilst France has reduced the net coal import in 2015 compared to 1990. Germany's net coal import has increased from 3.4 Mtoe to 36 Mtoe in 2015 compared to 1990, representing about 90% growth in 25 years. The UK has increased the net coal import from 8.5 mtoe to 14.5 Mtoe in 2015 compared to 1990, representing about 60% increase in 2015. France's reliance on coal has decreased from 12.8 Mtoe to 8.5 Mtoe in 2015 relative to 1990, representing about 35% decline in 2015. The net import of oil has decreased in Germany and France whilst the UK has increased the net oil import in 2015 relative to 1990. Germany and France reduced the net oil import by 12% and 9%, respectively in 2015 relative to 1990. The UK net import of oil has increased from -11 Mtoe to 27 mtoe in 2015 compared to 1990. Net import of natural gas increased in all three countries. The net natural gas import has increased by 30% in Germany and France whilst the UK has increased by 77% in 2015 compared to 1990.

3.4.4 Climate change mitigation - CO2 emissions reduction

The fig. 49 shows that CO2 emissions are gradually decreasing in Germany, France and the UK. The CO2 emission has reduced by 23%, 16% and 29% in Germany, France and the UK, respectively in 2015 compared to 1990. Germany has reduced the emissions from 940 MtCO2 to 729 MtCO2 in 2015 compared to 1990. France has reduced the CO2 emissions from 345 MtCO2 to 292 MtCO2, while the UK has reduced the emissions from 549 MtCO2 to 393 MtCO2 in 2015 compared to 1990.

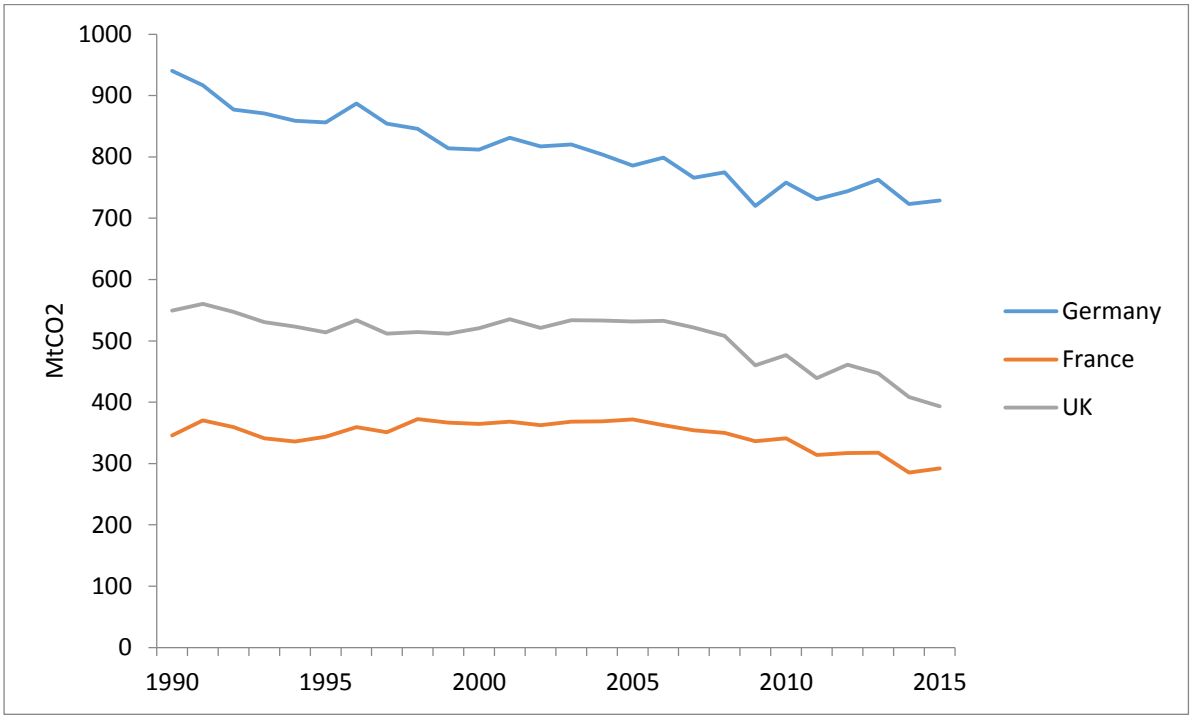

Fig.49 Annual CO2 emissions, 1990-2015 (Data source: IEA)

In 2015, electricity and heat sector is the largest source of CO2 emissions in Germany and the UK followed by transport, buildings and industry, whilst transport sector is the largest source of CO2 emissions in France followed by buildings, industry and electricity sector. It can be recognized by the fact that 75% of France's electricity comes from nuclear power which causes less emission and thus, the electricity sector in France is the lowest source of emissions. On the contrary, Germany and the UK are dependent on coal for electricity generation. Since coal has high CO2 emission factor, electricity sector emits large amounts of CO2. In recent years, the UK has reduced the use of coal in electricity generation, which has

resulted in the reduction of CO2 emissions from electricity sector, it decreased from 45% to 42% in 2015 compared to 1990. France also reduced CO2 emissions from 18% to 13% in 2015 relative to 1990. In contrast, Germany has increased the use of coal, as a result, CO2 emissions from electricity sector has increased from 44% to 49% in 2015 relative to 1990.

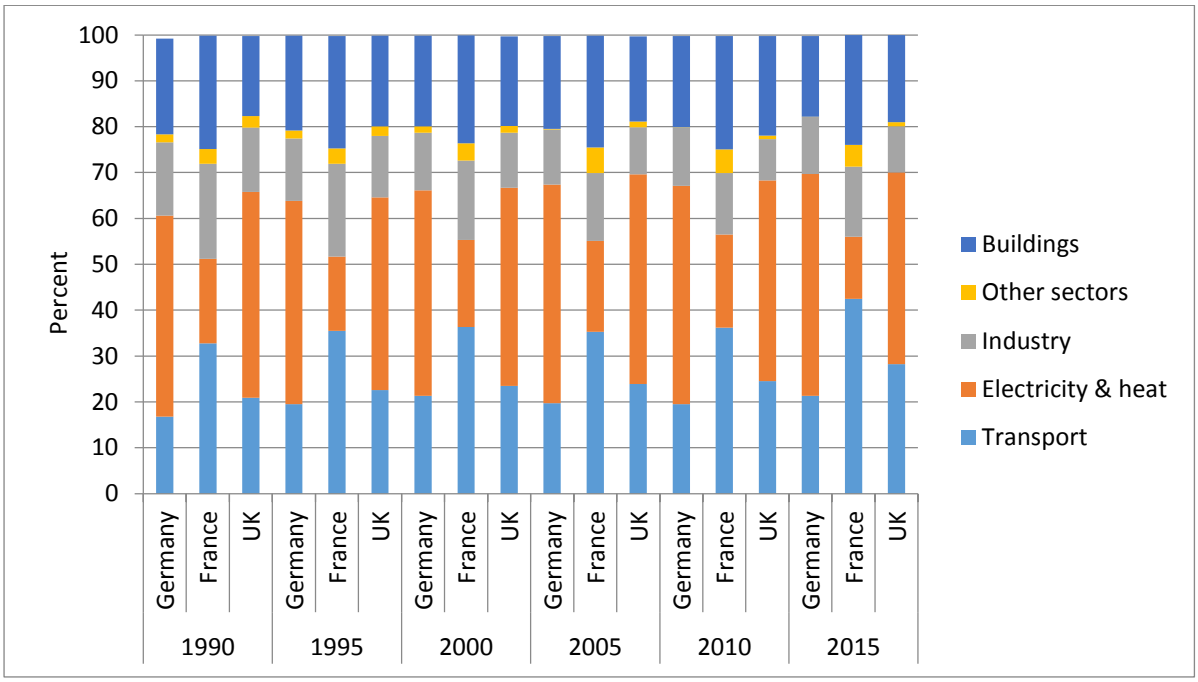

Fig. 50 CO2 emissions by sector (Data source: IEA)

Transport sector is the largest source of CO2 emissions in France. France's transportation demand is highly dependent on oil. Oil also has high emission factor which produces high CO2 emissions. France has increased the electricity sector's CO2 emissions from 38% to 42% in 2015 compared to 1990. In Germany and the UK, transport sector is the second largest source of CO2 emissions. Both the countries are also dependent on oil to meet their transport demand. Germany has increased the transport sector's CO2 emissions from 17% to 21% whereas the UK has increased the CO2 emissions from 21% to 28% in 2015 relative to 1990.

Building sector is also one of the largest sources of CO2 emissions. Germany and France has reduced the building sector's CO2 emissions while the UK has increased the emissions in 2015 compared to 1990. Germany has reduced the CO2 emissions from 21% to 17% from the building sector while France has reduced the emissions

from 25% to 24% from the building sector in 2015 compared to 1990. The UK has increased the CO2 emissions from the building sector from 17% to 19% in 2015 compared to 1990.

Industry sector is the lowest source of CO2 emissions in Germany and the UK, whereas for France, the industry sector is the second lowest source of CO2 emissions in 2015. All the countries have reduced the CO2 emissions in the industry sector in 2015 compared to 1990. Germany has decreased the CO2 emissions from 16% to 12.5%, France has reduced the emissions from 20.5% to 15.5%, and the UK has reduced the emissions from 14% to 10% from the industry sector in 2015 compared to 1990.

3.4.5 Renewables in electricity generation

Renewables has an important role in the pathway towards decarbonisation. Germany, France and the UK have increased the share of renewables in the energy supply mix in 2015. Germany and the UK have increased the renewable energy sources by 87% and 94%, respectively while France has increased the renewables about 29% only in 2015 compared to 1990. In Germany, the share of renewables in the energy mix has increased from 1.7% to 13.5 % in 2015 compared to 1990. The UK has increased the share of renewables from 0.5% to 8.5% in 2015 relative to 1990. France also has increased the renewables share in the energy supply mix from 6.7% to 9.4% in 2015 compared to 1990. In three countries, France (6.7%) has the highest share of renewables in the energy mix in 1990, whereas in 2015, Germany (13.5%) has the highest share of renewables in the energy mix.

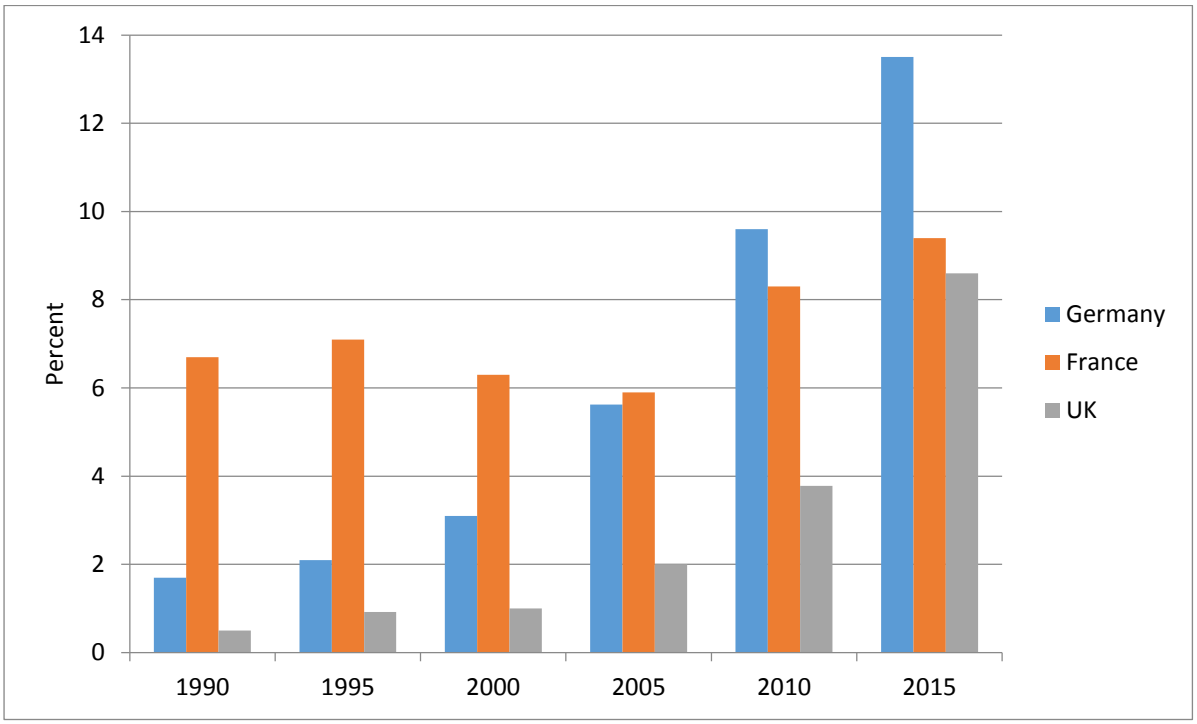

Fig. 51 Renewable energy in total primary energy supply, 1990 to 2015 (Data source: IEA)

Coal was the main source of electricity generation for Germany and the UK in 1990. Germany has 58% of coal share in the electricity generation while the UK has 64% of share of coal in the electricity generation in 1990. The United Kingdom has reduced the one-third of coal share in 2015 whereas Germany reduced the share of coal to 44% in 2015. France has only 2% of coal share in the electricity generation in 2015. Natural gas is the main source of electricity generation for the UK. The UK has increased the gas share from 1.5% to 29% in 2015 compared to 1990. Germany also relied on natural gas for generating 10% of electricity in 2015. France produced only 3.5% of electricity from natural gas in 2015.

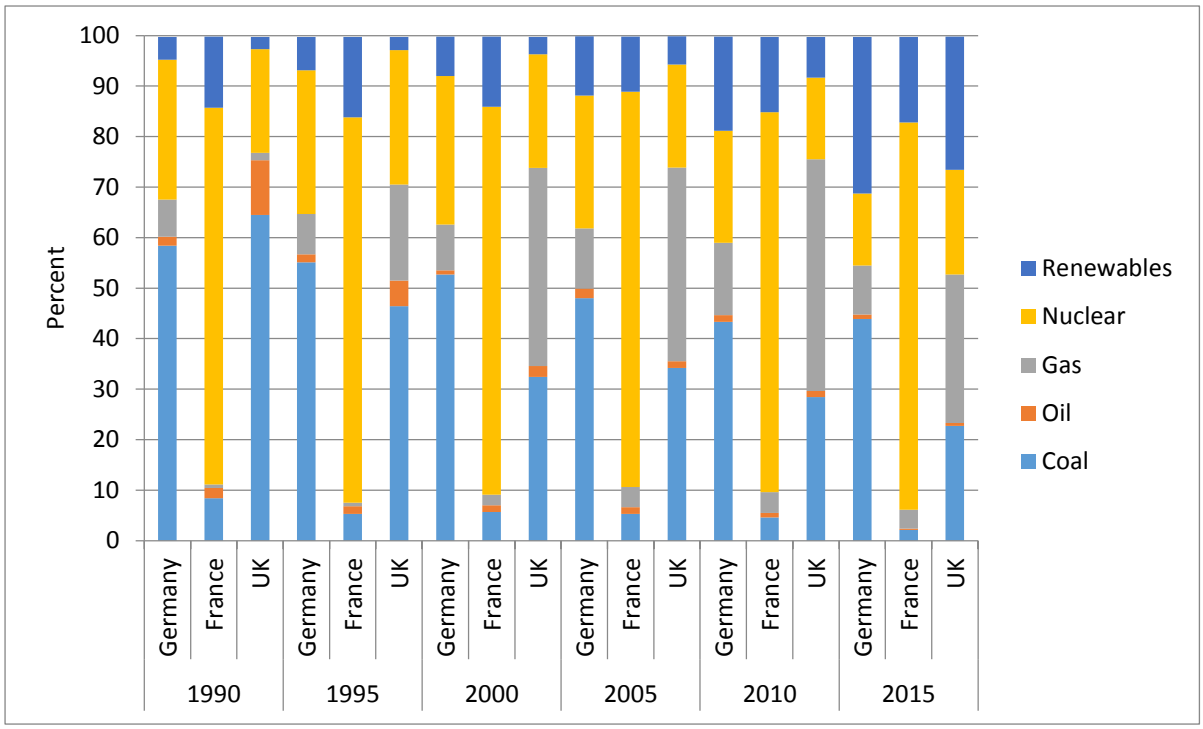

Fig.52 Electricity generation by fuel, 1990-2015 (Data source: IEA)

Nuclear is the main source of electricity generation for France. More than 75% of electricity generated from the nuclear in 2015. Germany and the UK generated only 14% and 21% of electricity from nuclear. Germany has reduced the half of the nuclear share in the electricity generation in 2015 compared to 1990. It is expected that the nuclear share in the electricity generation will continue to decline by 2022 after the German government decision to shut down nuclear plants. The share of renewable energy sources in the electricity generation has increased in all three countries. The share of renewables in the electricity mix has increased to 31% and 27% in Germany and the UK, respectively in 2015. France has increased the share of renewables in the electricity from 14% to 17% in 2015 compared to 1990.

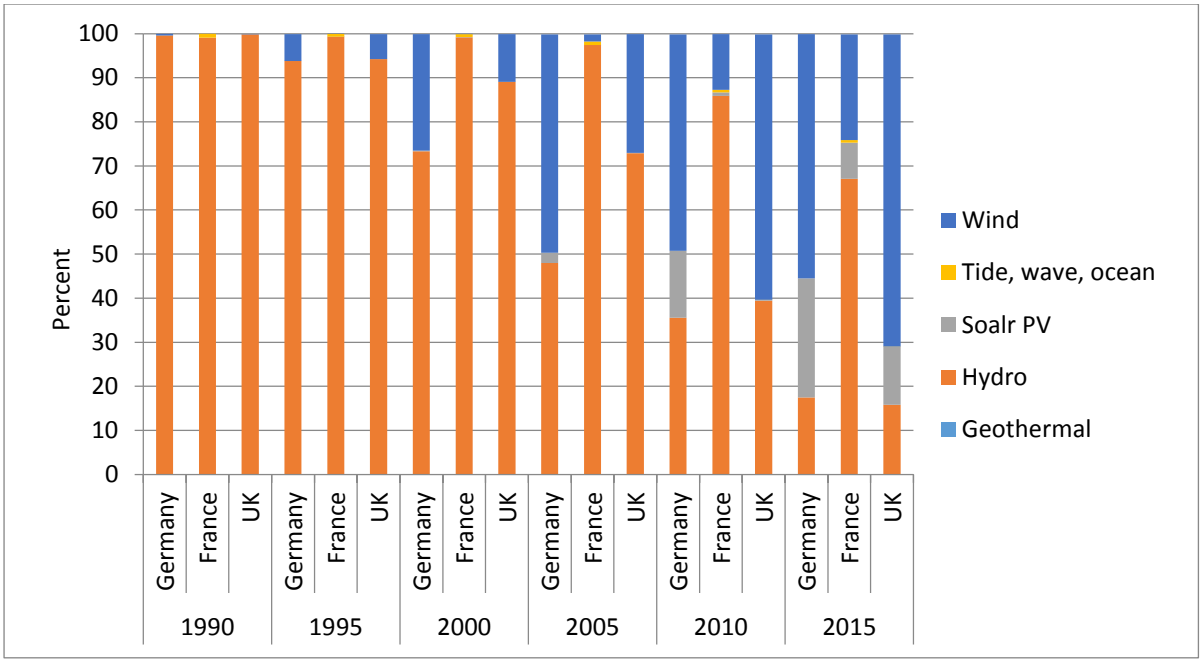

Fig. 53 Electricity generation from renewables by source, 1990 – 2015 (Data source: IEA)

The fig. 53 provides a breakdown of electricity generation from renewables by source. Hydro was the main renewable energy source to generate electricity in the 1990s. About 100% of electricity was generated from the hydro in all three countries. In the last two and a half decades, the electricity mix of renewables has changed drastically. In 2015, France has 65% share of hydro in the renewables electricity mix, whilst Germany and the UK reduced the share of hydro to 17% and 16%, respectively. Wind energy has replaced hydro energy to generate electricity from the renewables in Germany and the UK. About 70% and 55% of electricity generated from the wind in the UK and Germany, respectively in 2015. France has 24% share of wind in the renewables electricity mix in 2015. The solar PV has made paid progress in German renewables electricity mix. About 27% of electricity generated from the solar PV in 2015. The UK and France has 13% and 8% share of solar PV in the renewables electricity mix, respectively in 2015.

CHAPTER 4

MODELLING FRAMEWORK

In the 21st century, one of the main energy sector challenges is to reduce the GHG emissions as well as to meet the growing energy demand. To do this, the country needs to change its energy system and design a decarbonisation roadmap to keep climate change below 2°C. The current energy system is primarily based on fossil fuels which produce large amount of CO2 emissions and are responsible for climate change. The reduction of CO2 emissions can be addressed through decarbonizing the energy system while changing the fuel mix and reducing the growing energy demand.

The country's efforts on decarbonisation can be understood by seeing the decrease in emissions and the growth of renewable energy sources. In this context, a number of energy and climate targets have been set in many countries including Germany, France and the UK. These countries have already placed themselves on a transition towards a low-carbon economy through the establishment of energy transition plans to address the climate change and energy security challenges, and set targets for both short term (2030) and long term (2050) to reduce GHG emissions. For instance, energy transition plan in Germany "Energiewende" aims to reduce the GHG emissions by 55% and 80-95% until 2030 and 2050, respectively relative to 1990. The German government developed the 'Energy Concept' in 2010 by outlining long-term targets and objectives for a low carbon economy by 2050. France adopted its first energy transition plan in 2015 through the establishment of the 'French Energy Transition and Green Growth Act', which laid out ambitious short term and long term targets to reduce GHG emissions by 45% and 75% until 2030 and 2050, respectively compared to 1990 levels. The UK 'Climate Change Act' 2008 established a short term and long term decarbonisation targets to reduce greenhouse gas emissions by 50% and 80% until 2030 and 2050, respectively compared to 1990 levels.

The study focuses on Germany, France and the UK energy system, where the scenarios are developed while considering CO_2 emissions from the combustion of fossil fuels (coal, oil and natural gas), which are the key driver of climate change.

'Carbon dioxide emission factor' metric is being used to calculate CO_2 emissions from various fossil fuel sources. CO_2 emission factor is measured as "the quantity of CO_2 emitted (in kilograms) per unit of energy produced (in Megawatt-hours)"[13]. Emission factors for coal, oil and natural gas vary significantly and calculated from DEFRA emission conversion factors[14]. In this study, the fuel emission factors of the UK[15] have been considered i.e. coal - 3.25$MtCO_2$, oil - 3.05 $MtCO_2$ and natural gas 2.32 $MtCO_2$.

In light of the above, Germany has to cut fossil-fuel emissions from the 560 million tons of CO_2 ($MtCO_2$) in 1990 to 252 $MtCO_2$ and 112 $MtCO_2$ in 2020 and 2050, respectively in order to achieve the 55% and 80% CO_2 emission reduction targets. In the same manner, France can only afford to emit a maximum of 167 $MtCO_2$ and 76 $MtCO_2$ fossil-fuel emissions by 2030 and 2050, respectively compared to 305 $MtCO_2$ emissions in 1990 to meet the 45% and 75% emission reduction targets. The UK CO_2 fossil fuel emissions can't be more than 160 $MtCO_2$ and 63 $MtCO_2$ in 2030 and 2050, respectively compared to 320 $MtCO_2$ emissions in1990 for achieving 50% and 80% emission reduction targets.

To achieve these objectives and targets, it requires decarbonizing the energy system including the changes in primary energy consumption and final energy consumption. In addition to the climate protection challenges, there are some more challenges for these countries that need to be addressed in their energy system in 2030 and 2050. They are:-

- Ensuring energy security through reducing dependence on import of fossil fuels
- Increasing energy efficiency in order to decrease the final energy consumption.
- Increasing renewable energy sources
- Decarbonizing electricity sector

[13] CO2 emission factor - https://ourworldindata.org/fossil-fuels#greenhouse-gas-emissions-from-fossil-fuels

[14] DEFRA emission conversion factors – Available at https://www.gov.uk/government/collections/government-conversion-factors-for-company-reporting

[15] UK fuel emission factors - Digest of UK Energy Statistics, UK GHG emission factors, National Emissions Inventory

This chapter demonstrates and investigates the decarbonisation of the energy sector. The energy system of Germany, France and the UK are being modeled taking into account all energy supply sources and three main end-use sectors i.e. Industry, transport and buildings are also being considered.

The research applies the Kaya identity[16] or IPAT identity approach for analyzing the impact of energy system on GHG emissions. Impact, Population, Affluence and Technology (IPAT) is a model describes the level of energy use on CO_2 emissions. This equation developed by the Japanese energy economist Yoichi Kaya.

$F = P * (G/P) * (E/G) * (F/E)$

In the equation, "F" is GHG emissions, "P" is population, "G" is Gross Domestic Product (GDP), and "E" is energy consumption. Here, the three factors are not independent of one another, but multiplicative where impact is a function of population x affluence x technology.

LEAP[17] Modelling tool, DECC calculator[18] and Excel spread sheet model have been used for the analysis of energy system and the scenarios are developed for 2030 and 2050. Two scenarios are developed for two different target years, i.e. short term targets in 2030 and long term targets in 2050. These target years are driven by international agreements, EU goals and national energy transition plans, where 2030 targets are being chosen according to the goals of Paris Agreement and 2050 targets are aligned with national energy transition plans. The scenarios are designed based on data inputs and model assumptions. The aim of this scenario modeling is to design the low carbon energy system for 2030 and 2050 in order to achieve the CO_2 emission reduction targets while maintaining the country's energy security.

[16] Kaya Identity – Available at https://unfccc.int/files/adaptation/application/pdf/2.4_cicero_peters.pdf

[17] LEAP – Long-range Energy Alternatives Planning System

[18] DECC- The energy calculator DECC 2050 was created by the UK's Department of Energy and Climate Change (DECC) to explore the options for reducing emissions to 2050.

4.1 Scenario design characteristics and modelling assumptions

- The scenarios for 2030 and 2050 are designed with a base year of 2015.

- In both the scenarios, two main objectives and targets are considered i.e. energy security and CO2 emission reduction.

- The data has been collected from multiple sources including Nationally Determined Contributions (NDCs); National energy transition plans; EU energy policies. In addition, Department of Energy and Climate Change (DECC); Energiewende; Eurostat; Clean Energy Wire; and Climate Analytics were also referenced. For data on energy supply and demand, energy balances, Sankey diagram, the OECD and International Environment Energy (IEA) database were used. For population and GDP, data was collected from the World Bank database.

- The scenarios build on current trends; projections on population and GDP growth; NDCs targets; EU energy and climate policies; national energy transition plans; and recent government decisions. It also assumes that existing policies and transition plans will be strengthened with a strong implementation measures, as well as new policy measures will be introduced in the coming years. Fuel prices are not included in this model.

- The scenarios are also being modeled with consideration of key energy strategies such as energy efficiency enhancements; expansion of renewable energy sources (RES); electrification; fuel switching; security of supply; low-carbon supply technologies; and end-use sectors innovations.

- Different low carbon energy supply technologies are considered for the 2030 and 2050 scenarios such as coal-fired generation using carbon capture and storage (CCS); bioenergy technology in the power, heating and transport sector; solar PV, wind and marine renewables technology; and fuel cell technology.

- It also assumes that future energy demand decrease due to energy conservation, energy efficiency, technological innovation, environmental awareness, and changes in lifestyle.

- Germany coal plants will be in use by 2038, while the UK coal plants will be phased- out by 2025.

- Germany will phase out nuclear plants by 2022 and thus in both 2030 and 2050 scenarios, nuclear power plants are not considered. A significant number of UK's existing nuclear power plants are going to be retired in the coming years and the UK government will build new nuclear plants. France will reduce the nuclear share from 75% to 50% in its electricity mix.

- The final energy consumption is likely to be met by RES, which will continue to grow rapidly and likely to replace fossil fuels completely by 2050.

4.2 Scenario development

The scenarios are being developed and evaluated by using the following five energy transition elements:

a) Energy supply side
b) Energy demand side
c) Climate change mitigation - CO_2 emissions reduction
d) Energy security - Security of supply
e) Renewables in electricity generation

4.2.1 Energy supply side

Decarbonisation in energy supply can be achieved through a phase-out of coal, low dependence on oil and natural gas fuels, advancements in nuclear power and CCS technology, and improvements in energy efficiency and renewable supply technologies. Pursuing these measures helps to achieve low-carbon energy system objectives for both short term and long term targets.

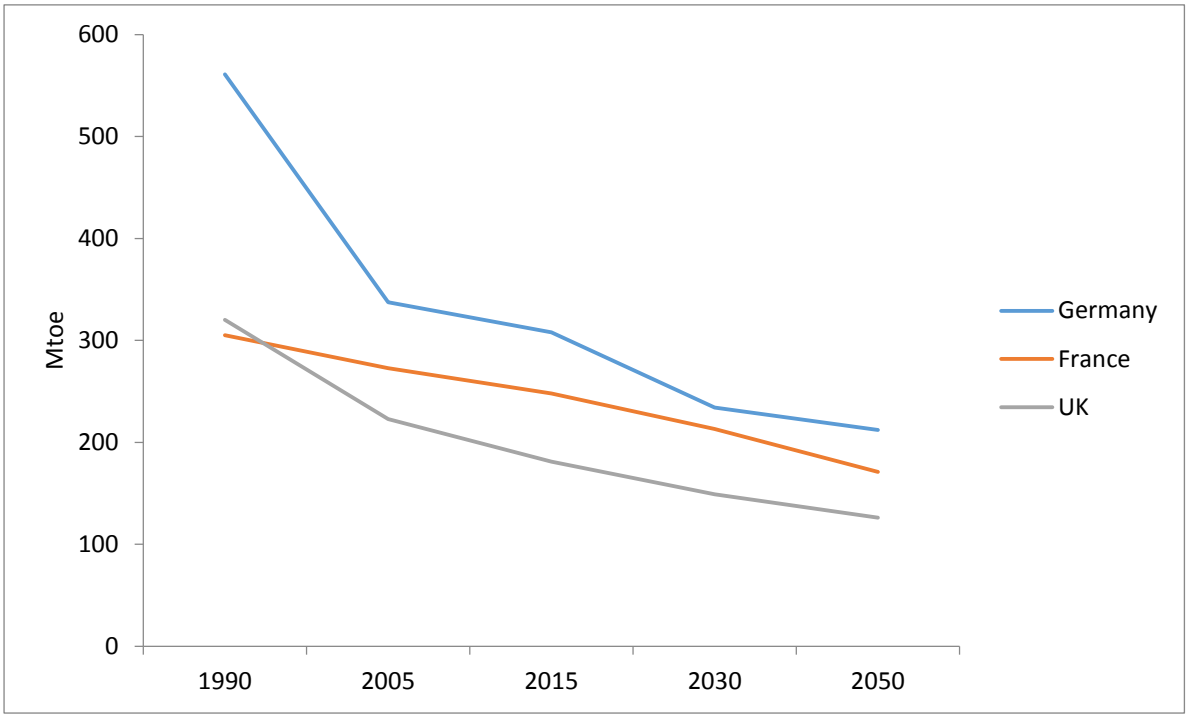

Fig.54 Total Primary Energy Supply (TPES), 1990-2050

The scenario of 2030 and 2050 shows that the total primary energy supply (TPES) will fall, which is driven by energy efficiency policies as well as the deployment of smart grids. In 2050 the supply of fossil fuel is reduced, which will be compensated by renewable energy sources. Thus, the energy supply mix of these countries looks differently by 2050 due to switching over to the renewables. In Germany, the total primary energy supply decrease from 312 Mtoe to 234 Mtoe in 2030, representing a decline of 24% compared to 2015. This primary energy supply further slips to 32% in 2050. In France, the TPES falls from 248 Mtoe in 2015 to 171 Mtoe in 2050, decreases 30% relative to 2015 levels. The UK primary energy supply declines to 149 Mtoe and 126 Mtoe in 2030 and 2050, respectively, representing 18% and 30% decline compared to 2015.

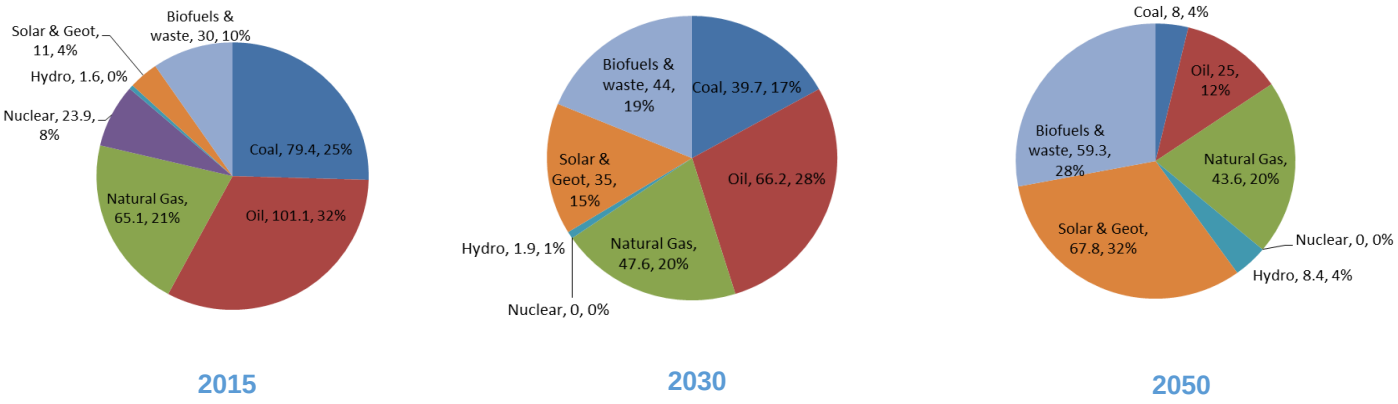

Fig.55 TPES by source – Germany, 2015-2030-2050

The scenario model explores both fossil and non-fossil fuels supply options. The total primary energy supply (TPES) sectors can be classified and examined as follows:-

Coal – Coal plays an important role in the country's energy mix and electricity mix. In order to achieve the decarbonisation targets, there is a need to reduce dependence on coal and increase CCS technology in power plants. Due to high CO_2 emission factor, coal is a main driver of climate change. The share of coal declines to a minimum by 2050 in all these three countries, whilst in 2030 scenario, the coal share lies in the range between 2% to 17%, where Germany and France are the highest and lowest consumption of coal, respectively.

In Germany, coal accounted for 37% of total energy supply in the 1990. Since 1990, the share of coal has declined to 25% in 2015, and recently, Germany has decided to phase-out the coal by 2038. Therefore, in the 2030 scenario, it assumes that no new coal plants will be constructed while existing coal plants will be decommissioned as per their lifetimes.

In France, the supply of coal has been very low since 1990, which gradually decreased by 2015, wherein the coal decreased from 20 Mtoe to 8.8 Mtoe in 2015 relative to 1990 levels. The scenario results show that in 2030 the coal supply continues to fall, where it reaches 3 Mtoe and further slips to the lowest 1.2 Mtoe in 2050. In contrast, in the UK, coal was supplied in large quantities during 1990s, which has changed significantly after adopting the Climate Change Act Law in 2008. The coal supply declined significantly from 63 Mtoe to 24 Mtoe in 2015 compared to 1990. The result displays that supply of coal declines up to 9 mtoe in 2030, which further reduces to a minimum of 4 Mtoe in 2050.

Oil – In all the three countries, oil is the dominant energy source mainly in the transport sector, where 98% of the transport sector depends on the oil supply. Germany accounted for 101 Mtoe oil in 2015, which reduces to 66 Mtoe and 35 Mtoe in 2030 and 2050, respectively. From 2030, there will be a significant change in the supply of oil in the energy mix, where over 80% of the oil in transport will be replaced by electricity or other fuels. In the same manner, France and the UK dependence on oil significantly decreases, where France's oil supply declines from 72.2 Mtoe to 21 Mtoe in 2050 compared to 2015 and the UK declines the oil consumption from 60 Mtoe to 27 Mtoe in 2050 relative to 2015.

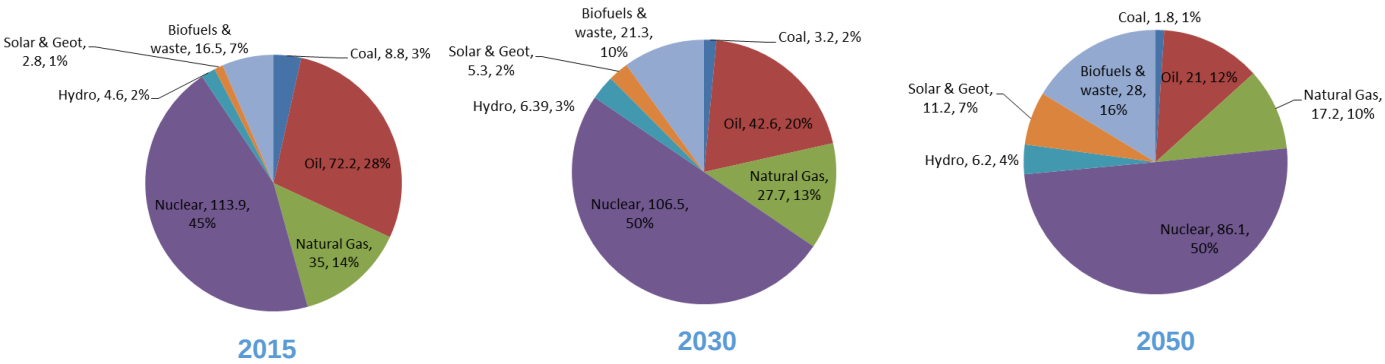

Fig.56 TPES by source – France, 2015-2030-2050

Natural gas – Natural gas is the important fossil fuel source which has the lowest CO2 emission factor. Although three countries are heavily dependent on gas imports, the share of natural gas in the TPES is higher than coal and oil. In Germany, the gas supply accounted for 65 Mtoe in 2015, which reduces to 47.6 and

43.6 Mtoe in 2030 and 2050, respectively. France gas consumption amounted to 35 Mtoe in 2015, which reduces to 27.7 Mtoe and 17.2 Mtoe in 2030 and 2050, respectively. The UK gas supply share slightly declines from 35% to 30% in 2050 compared to 2015. In 2015, the gas supply amounted to 61.7 Mtoe which fell to 36.4 Mtoe in 2050.

Nuclear – In the future primary energy consumption, Germany declines its nuclear share in the TPES whereas France increases its share in TPES to 50%. In Germany, nuclear share drops to zero in 2030 due to the government decision to phase-out nuclear plants by 2022 after the Fukushima nuclear accident in 2011. The nuclear policy was revised in the same year and made a decision to phase-out all the nuclear plants by 2022. Therefore, it is assumed that in both scenarios no new nuclear plant can be built, due to which nuclear contribution becomes zero from 23.9 Mtoe in 2015.

France energy supply mix is highly dependent on nuclear. Although France increases its nuclear share in the TPES, the nuclear capacity decreases slightly in 2030 from 113 Mtoe in 2015 to 106 Mtoe in 2030. The French government also contemplated the decline in nuclear capacity in the long run. France aims to reduce the nuclear share from 75% to 50% in the electricity mix by 2025 (French Energy Transition Law). Thus, in the 2050 scenario, it assumes that less new nuclear plants will be built after 2030, resulting in the reduction of nuclear capacity to 86 mToe in 2050.

In the UK, the nuclear supplies increase where it reaches 20 Mtoe in 2030 from 18 Mtoe in 2015. However, the further penetration of nuclear supplies declines to 14.5 Mtoe in 2050. The main reason for the initial rise in nuclear supply in 2030 is concern of energy security. This is because the UK government has decided to shut down coal plants by 2025 and therefore the energy supply should be compensated by other low carbon fuels i.e. nuclear or gas. The UK recognizes the role of nuclear power in achieving 2030 decarbonisation targets and therefore increases the investment in nuclear supply. Moreover, currently, renewable growth in the UK is minimal and its development in the initial stage. In this context, nuclear is the only

non-fossil fuel option which helps in achieving 2030 emission reduction targets. After 2030, most of the nuclear fleet will be retired and government has no plan to build new nuclear plants. Therefore, the nuclear share drops by 2050 and it will be replaced by renewable energy sources, which is a 2.5-fold increase from 15 Mtoe to 40 Mtoe in 2050 compared to 2015.

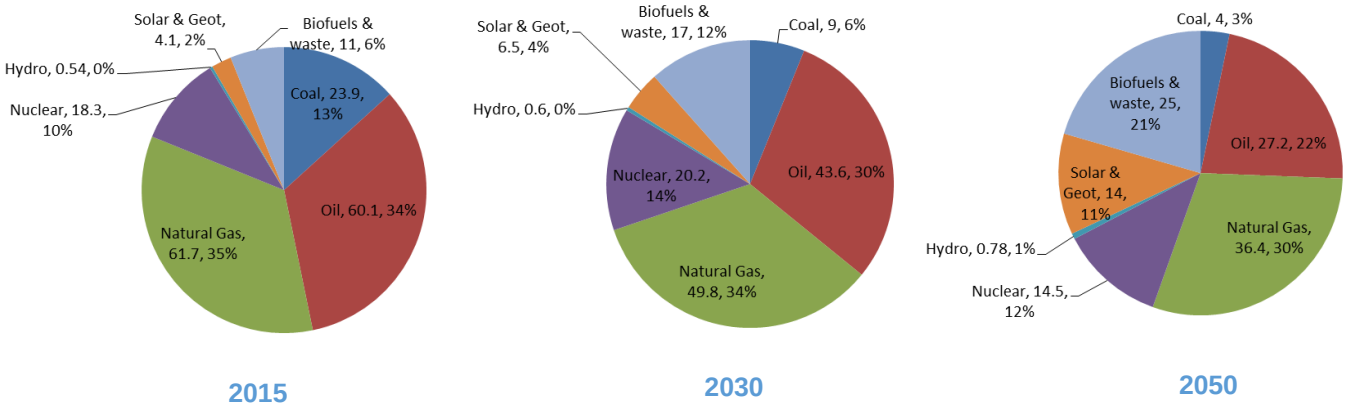

Fig.57 TPES by source – United Kingdom, 2015-2030-2050

Renewable energy sources (**RES)** – Renewables are a key component in a decarbonsaition process and its contribution is enormous in the future primary energy mix. Although, at present, renewable energy has a minor share in the energy mix, RES share make up between 27% and 64% in TPES by 2050 in these countries; where Germany and France share the highest and lowest renewables. Biofuels continues to be the highest share of renewable source in 2030 and 2050.

In Germany, the renewable share in TPES rises strongly by 2030, reaching 34% under the current policies and substantially increases to reach 60% in 2050. In 2015, the total RES including biofuels and solar amounted to 42.6 Mtoe, representing 14% of TPES. The RES supply almost doubled to 80.9 Mtoe and 3.5 times increase to 135.5 Mtoe in 2030 and 2050, respectively.

Unlike Germany, France is more dependent on nuclear in terms of clean energy supply. France also increased its renewable capacity, where the total RES amounted

to 23 Mtoe in 2015 doubled to 46 Mtoe in 2050. The UK renewable growth pattern is similar to France. In 2015, the total RES amounted to 15 Mtoe, which increases to total 24 Mtoe in 2030 and 40 Mtoe in 2050. In the UK, it assumes that the biomass plant will be replaced by existing coal plants, which helps in increasing the renewables capacity. Offshore and onshore wind capacity also gradually increases.

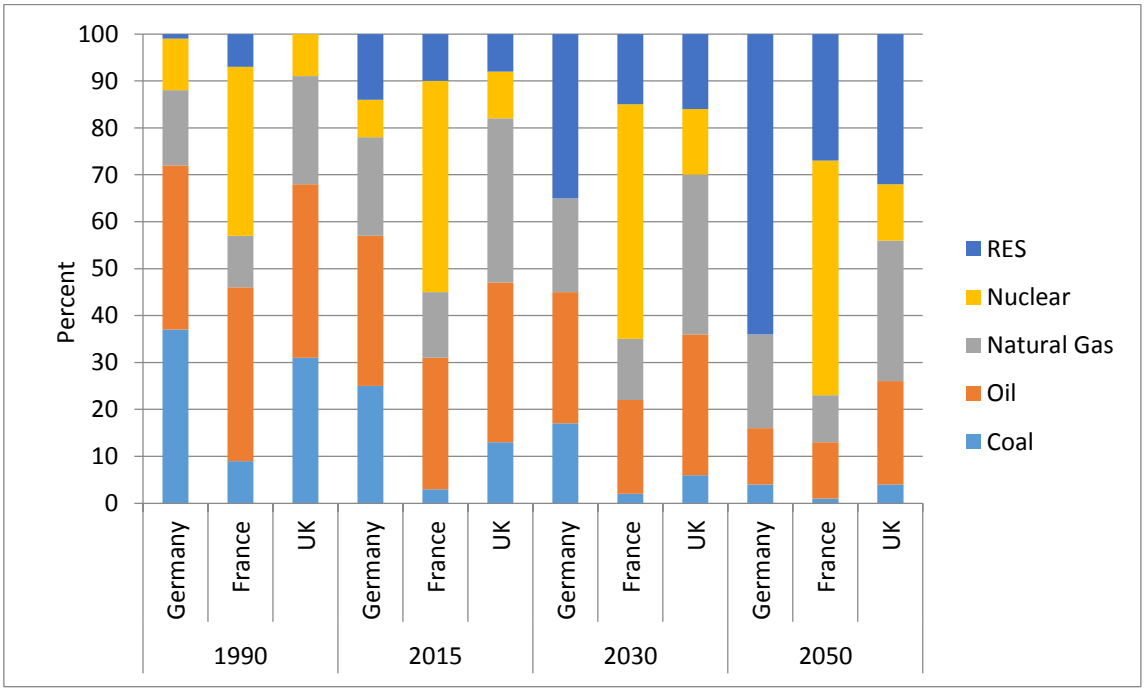

Fig. 58 Fuel shares in TPES, 1990--2050

The fig. shows comparison of fuel shares in total primary energy supply.

- Coal share drops below 5% in 2050 in all three countries. In 2030, the share of coal declines significantly; Germany loses maximum 12 points, but still has the highest share (17%) in energy supply mix among the three countries. France reaches only 2% of the shares, where the UK represents a 6% share in the energy supply mix.

- Oil share falls to 12% in both Germany and France, whereas UK oil shares reach 22% in energy supply mix by 2050. In 2030, oil shares in these

countries are in the range of 20-30% of TPES, where the UK shares the maximum 30%.

- Natural gas reduces minimum of all fossil fuels; Germany gas share in TPES is almost steady that make up between 20-22% in 2030 and 2050; France and the UK gas share in 2030 also remains stable with a 14% and 34% of TPES, respectively, loses 4 and 2 points compared to 2030 and reaches 10% and 32%, respectively by 2050.

- The shares of nuclear in TPES significantly vary in three countries. France energy supply will be dominated by nuclear whereas Germany will be phased-out the nuclear in its energy supply by 2022. This phase-out decision made by the German government after the Fukushima nuclear accident in 2011. France nuclear share increases and reaches 50% by 2030 and 2050 compared to 46% in 2015; UK also increases its nuclear share in 2030 and gains 4 points from 1990, represents 14% in TPES, which falls to 12% in 2050.

- RES dominance in the energy supply mix starts from 2030 and peaks at 2050; maximum increase can be seen in Germany with a 64% share in TPES by 2050. Germany renewable share in TPES was only 14% in 2015, which increases to 35% in 2030 and 64% in 2050; France renewable share in TPES is the lowest in three countries i.e. 10%, 15% and 27% in 2015, 2030 and 2050 respectively; The UK RES share increases two-fold in 2030 and four fold in 2050 compared to 8% in 2015.

4.2.2 Energy demand side

In general, there are three key sectors in country's economy which make up a large part of its energy consumption. These sectors are industry, transport and buildings and are also called end-use sectors. Decarbonisation in the end-use sectors can be achieved through a reduction in the final energy consumption. Energy demand depends mainly on the demographic profile

and economic activity. However, energy efficiency, technological innovation, fuel switching and behavioural change are key drivers of energy demand reduction in the end-use sectors.

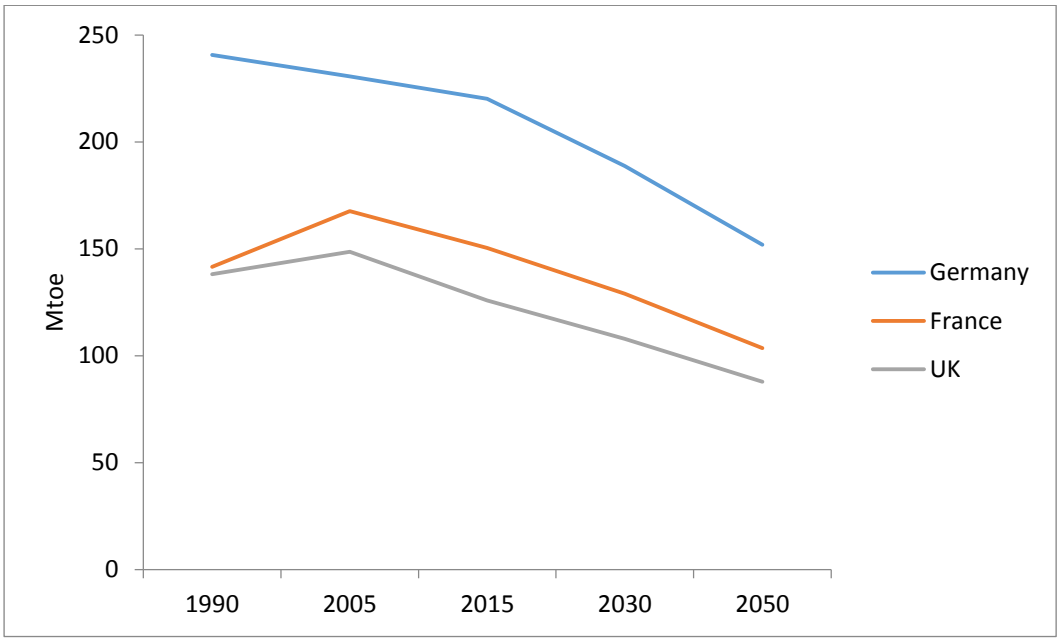

Fig. 59 Total Final Consumption (TFC), 1990-2050

Total final energy consumption is projected to be decreased gradually by 2050. Germany final energy consumption was hovering above 200 Mtoe and reached 220 Mtoe in 2015. The other two countries final consumption was lower than Germany, where France and the UK accounted for 150 Mtoe and 126 Mtoe, respectively in 2015. The scenario result shows that Germany final energy consumption reduces to 188 and 152 Mtoe in 2030 and 2050, respectively. France energy demand reduces to just above 100 Mtoe in 2050, whilst the UK final demand decreases to well below 90 Mtoe in 2050. A reduction in final energy demand becomes possible due to improvement in energy efficiency, electrification and technological innovation in end-use sectors.

End-use sectors

i) Industry sector

Industry sector ranked at the bottom in three major sectors. Carbon Capture and Storage (CCS) plays an important role in the decarbonisation process of industry sector. In the scenario it assumes that CCS captures 45% of industry's CO2 emissions. Additionally, energy efficiency improvements, fuel switching from fossil fuels to biofuels and electrification are key drivers to decarbonize the carbon-intensive industry sector.

In 2015, industry sector accounted for 25% of final energy consumption in Germany, whilst France and the UK accounted for 18% of final energy consumption. In Germany, the industry demand amounted to 55.2 Mtoe in 2015, which reduces to 47.3 Mtoe and 36.7 Mtoe in 2030 and 2050, respectively. France and the UK industry demand amounted to 26.7 mtoe and 23.1 Mtoe, respectively in 2015, which falls to 17.7 Mtoe and 14 Mtoe, respectively in 2050.

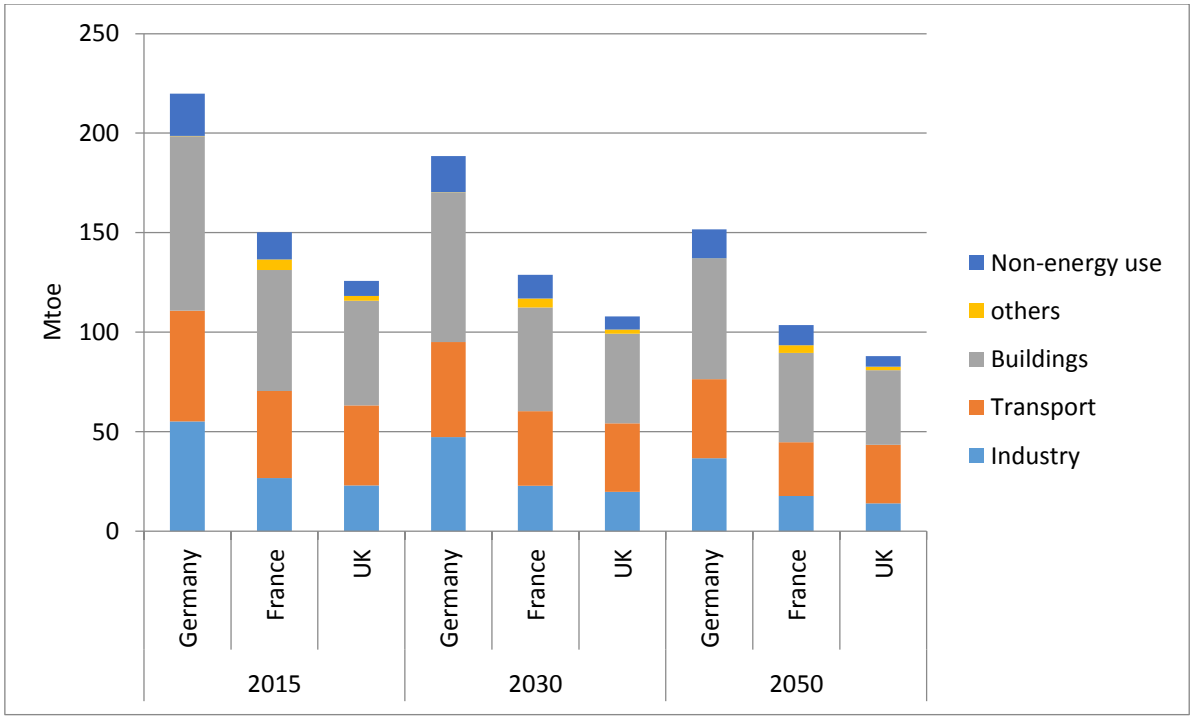

Fig.60 TFC by sector, 2015-2050

ii) Building sector (Residential and commercial)

Decarbonisation in the building sector is of utmost importance as this sector accounts for 40% of energy demand and represents one-fifth of global GHG emissions (IPCC 2014a). Building sector can play an important role in reaching 2030 and 2050 decarbonisation targets for Germany, France and the UK. This sector has a potential to curb the emissions by 60% by 2050 (Boardman et al., 2005). Energy efficiency measures, use of electric appliances and on-site renewable electricity generation are key drivers for decarbonising the building sector.

Building sector comprises both residential and commercial buildings. This sector requires ambitious efforts in order to achieve the 2030 and 2050 targets. Thus, in the scenario, it assumes that from 2015 onward all new buildings are zero-energy buildings and existing buildings will be retrofitted.

The fig. 60 shows that in Germany, the building sector energy demand reduces from 55.2 Mtoe to 47.3 Mtoe and 36.7 Mtoe in 2030 and 2050, respectively. France and the UK also reduce its demand from 60.7 Mtoe and 52.6 Mtoe in 2015, respectively to 44.8 Mtoe and 37.6 mtoe in 2050, respectively.

Building envelope and electronic products including lighting and appliances could play a decisive role in reducing final energy consumption in buildings. Lighting and appliances account for 60% of the electricity use in buildings (IEA 2016d). It is a trend that energy usage of these appliances increases with the population growth and GDP growth. In contrast, the scenario results of 2030 and 2050 shows decrease in final energy consumption. This is due to improving the energy efficiency of residential and commercial lighting and appliances and is governed by appliances standards and energy labeling programs. Furthermore, advancement of technological innovation also reduces the power consumption, which in turn, reduces the electricity demand of the electronic products. In the scenario, it assumes that electricity demand for lighting could be reduced between 15%-18% and 30-34% in 2030 and 2050, respectively.

Moreover, improving the performance of building envelope also decreases the final energy consumption in the building sector. All these countries have adopted building energy efficiency standards, especially PassivHaus standards[19]. PassivHaus standards developed in Europe based on the principles of – space heating and cooling energy demand, renewable primary energy demand, airtightness and thermal comfort. It entails that building envelope performance could be improved by minimizing heat loss and heat gain. Additionally, in the scenario, with an aim to improve the building envelope performance, building integrated photovoltaic (BIPV) and vertical greenery materials are used to replace the conventional building materials in the building fabric.

In addition to the energy efficiency measures, building technologies also has a crucial role to play to reduce the final energy demand. For example, smart technologies including smart grids and smart metering, electric technologies like heat pumps, renewable energy technologies, and other low or zero-carbon technologies are considered for 2030 and 2050 scenarios to reduce the final energy consumption.

iii) Transport sector

Transport plays a very important role in country's economy growth as well as quality of life for the people. The key drivers of transport demand are employment, education, healthcare, business travel, leisure trips, shopping, and friends and family. Transport is an important sector of the energy system, which needs to be decarbonised if the objectives of 2030 and 2050 targets are to be met. Transport sector accounted for 29% of final energy consumption in global energy system. Transport energy use has more than doubled in last 35 years. It was also responsible for a quarter of global energy related emissions in 2014, of which 75% came for road transport (IEA 2016b).

Transport sector accounts in the range of 25-30% of final energy consumption in these three countries. It is important to understand how energy is consumed in the transport system. Road transport is the dominant sub-sector for energy use and

[19] Passivhaus standard - Available at https://passiv.de/en/02_informations/01_whatisapassivehouse/01_whatisapassivehouse.htm

emissions in Germany, France and the UK. There are several key factors that are linked with the energy consumption of transport and emissions including travel activity levels, travel modes, vehicle efficiency, vehicle fuel sources, technology and power source, and behavioural factors. Transport demand and emissions can be reduced by reducing the level of activity, shifting the travel modes to public transport, improving the efficiency of the vehicle, switching to low carbon fuels, reducing the carbon intensity, diffusion of zero emission vehicle technologies, and changing in occupancy rates.

In the scenario building for transport sector, only domestic passenger transport has been considered. Freight transport and international aviation and shipping have not been considered in the scenario study. The scenario assumes the following key factors of transport energy use and CO_2 emissions: -

- **Passenger transport activity** – The 2030 and 2050 scenario assumes that in these countries there would be a shifts in mode of transport in the form of public transport and non-motorised transport (NMT) i.e. walking and cycling. The 'rebound effect'[20] has not been taken account in the scenarios. It would also be seen as increase in car pooling and increase in average number of people per vehicle. For example, average number of bus passengers per vehicles increases to 20, personal car travel drops by 25%, public road transport rises by 45%, rail travel increases by 40%, and cycling increases to 15% in 2050. It is also assumed that total distance travelled will be reduced by 5%, where more people starts working at home and long business trips will be replaced by teleconferencing.

- **Vehicle technology –** In 2050, these three countries will see a high rise in the electrification of transport. It assumes that 70% of internal combustion engine vehicles will be replaced by electric and fuel cell vehicles. To support electric and fuel cell vehicles, battery and hydrogen technology costs will also be significantly reduced.

[20] Samaras, Costa. 2013.The Rebound Effect in Transportation: Understanding the Important Implications for Climate Change. Available at https://cedmcenter.org/wp-content/uploads/2013/01/Costa-Samaras1.pdf

- **Vehicle efficiency –** It assumes that vehicle efficiency will be improved in both the scenarios. The efficiency will be improved by advancement in engines, lighter designs and technical improvements. Internal combustion engines vehicles and electric vehicles efficiency increases by 60% and 40%, respectively by 2050. Rail efficiency increases by 30% in 2050.

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In recent decades, there has been significant progress in transport technology particularly in UK and Germany. In the UK, since 1995, the car fuel efficiency has increased by 22%, where CO_2 intensity of vehicle i.e. carbon emissions were 150g CO2 per vehicle kilometre in 2010. Half of the rail network has also been electrified (Climate Action Tracker).

In both the 2030 and 2050 scenarios, transport demand is projected to decrease in Germany, France and the UK. In Germany, the transport energy demand declined by 14% and 32% in 2030 and 2050, respectively compared to 2015 levels. Oil is the main source for transport sector, which reduces to 48% and 90% in 2030 and 2050, respectively. In 2050, it assumes that transport demand will be compensated by biofuels and electric cars. France and the UK also follow a similar path to Germany, where their transport energy demand declines by 38% and 27% in 2050, respectively compared to 2015 levels. In future, France and the UK transport system will depend less on the fossil fuels. For example, in 2050, the consumption of fossil fuel declines by 94% in France and 92% in the UK compared to 2015. Biofuels and electric vehicles will compensate the transport demand, where biofuels represents 40% and 30% of transport energy demand in France and the UK, respectively in 2050. Remaining transport energy demand will be compensated by electricity, where electricity accounts for 50% and 60% of energy demand in France and the UK, respectively in 2050.

EU has set ambitious fuel economy standards for vehicles, according to which CO_2 intensity of vehicles i.e. average CO2 emissions per vehicle kilometer need to be 70 gCO2/vkm by 2030 and 30 gCO2/vkm by 2050 (Climate Action Tracker).The scenario results show that in the UK and France the transport emissions are likely to decrease by around 50% and 93% in 2030 and 2050, respectively compared to 2015. In Germany, the emission reduces by 48% and 90% in 2030 and 2050,

respectively compared to 2015 levels. In 2030 and 2050, the CO2 intensity of vehicles is within the reach of EU standards with the value of 68 gCO2/vkm and 27 gCO2/vkm, respectively. This is mainly driven by the adoption of stringent policy measures, modal shifts, fuel economy standards and technological innovation, which includes improvement in new vehicle fuel efficiency; switching to cleaner fuels; and increase in electric drive vehicles.

4.2.3 Energy security – Security of supply

Import dependency is one of the indicators of energy security and this makes a high energy transition goal for three countries. Germany, France and the UK are heavily dependent on import of fossil fuels for their electricity and transport needs. Energy efficiency improvements and renewable energy sources deployment are key drivers for reducing the fossil fuels import dependence.

The fig. 61 shows that in 2030, the net import dependence decreases in the range of 21-34% in these three countries, which is driven by decline in fossil fuel imports, decrease in total final energy consumption and increase in the use of domestic resources, especially renewables. Germany and France's import dependence declines by 31% and 34%, respectively in 2030 compared to 2015. In 2050, Germany's net energy import changes to a great extent and falls above 50% compared to 2015 levels, where France's net import falls by 56% due to the substantial use of domestic nuclear resources. The UK net energy imports do not change significantly in 2030 and 2050, where it falls to 21% and 35% in 2030 and 2050, respectively compared to 2015.

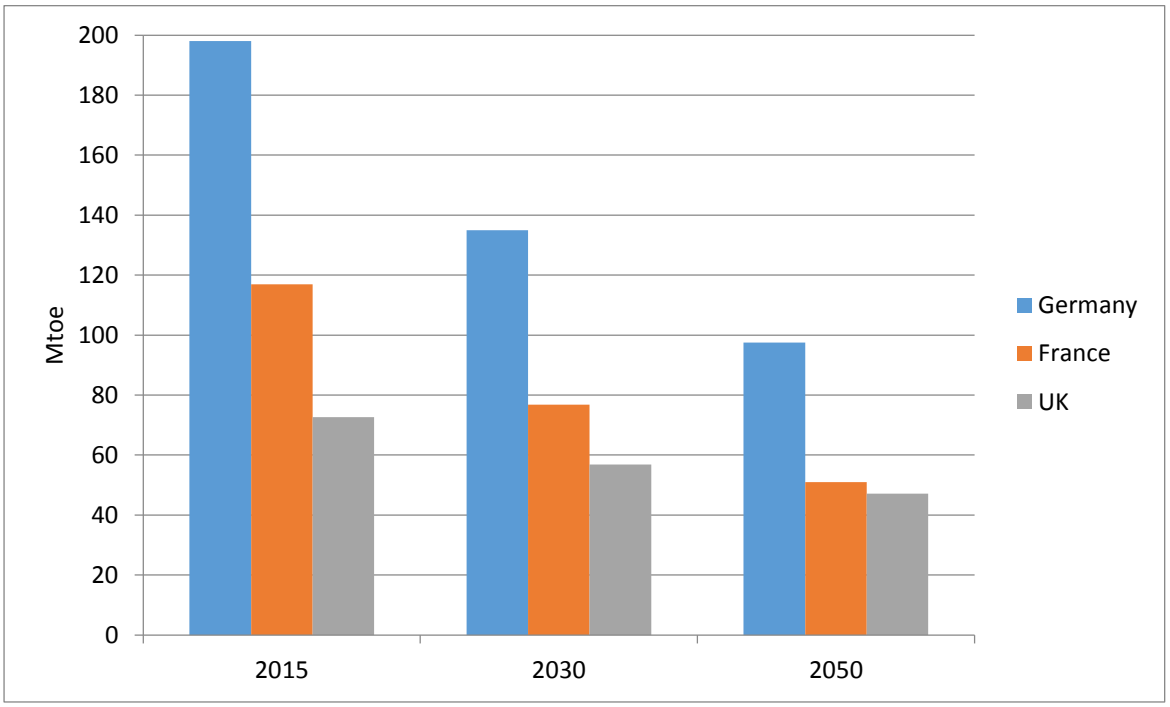

Fig.61 Net energy imports, 2015-2050

Germany, France and the UK are dependent on import of energy, mainly fossil fuels from the other countries. Germany's energy system is heavily dependent on imported fossil fuels. Germany imported over 95% of crude oil and 90% of natural gas from other countries in 2015. France also relied on imports of fossil fuels, particularly natural gas. However, in view of achieving decarbonisation targets in 2030 and 2050, the reliance on fossil fuels is likely to decrease in the future, which is driven by decline in energy demand and the increase in domestic renewable energy sources.

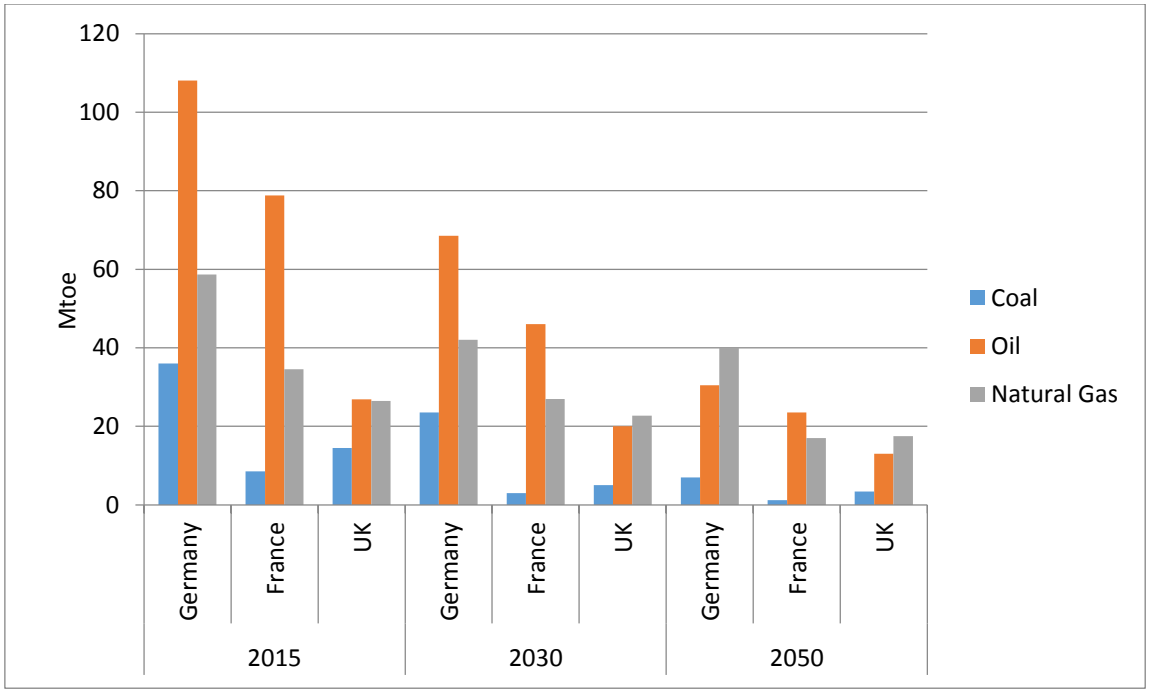

Fig.62 Net energy imports by source, 2015-2050

The fig.62 shows that in Germany, coal reliance drops from 36 Mtoe in 2015 to 23.5 Mtoe and 7 Mtoe in 2030 and 2050, respectively. The German government decision to phase out coal by 2035 will substantial reduces the coal import by 2050. France has imported marginal coal in 2015 that accounted for 8.5 Mtoe, which reduces to 3 Mtoe and 1.2 Mtoe in 2030 and 2050, respectively. France's energy will remain dependent on domestic nuclear resources, which imports less coal in the future. The UK coal dependence has started to decline from 2012 when the government adopted Climate Change Act, as a result, the reduction in coal imports will continue in the future, thus coal import declines to 5 Mtoe and 3.4 Mtoe in 2030 and 2050, respectively compared to 14.5 Mtoe in 2015.

Germany is highly dependent on oil import to fulfill its needs and imported over 95% of crude oil in 2015. France and the UK imported over 75% and 50% of crude oil in 2015, respectively. However, in 2030 and 2050, the import dependence of oil decreases in these three countries, mainly in Germany thanks to fuel switching from oil to biofuels, which is mainly used in the transportation sector. Germany oil import decreases from 108 Mtoe in 2015 to 68.5 Mtoe and 30.5 Mtoe in 2030 and 2050, respectively. France and the UK net oil import declines from 78.6 Mtoe and 27 Mtoe in 2015 to 23.5 Mtoe and 13 Mtoe in 2050, respectively.

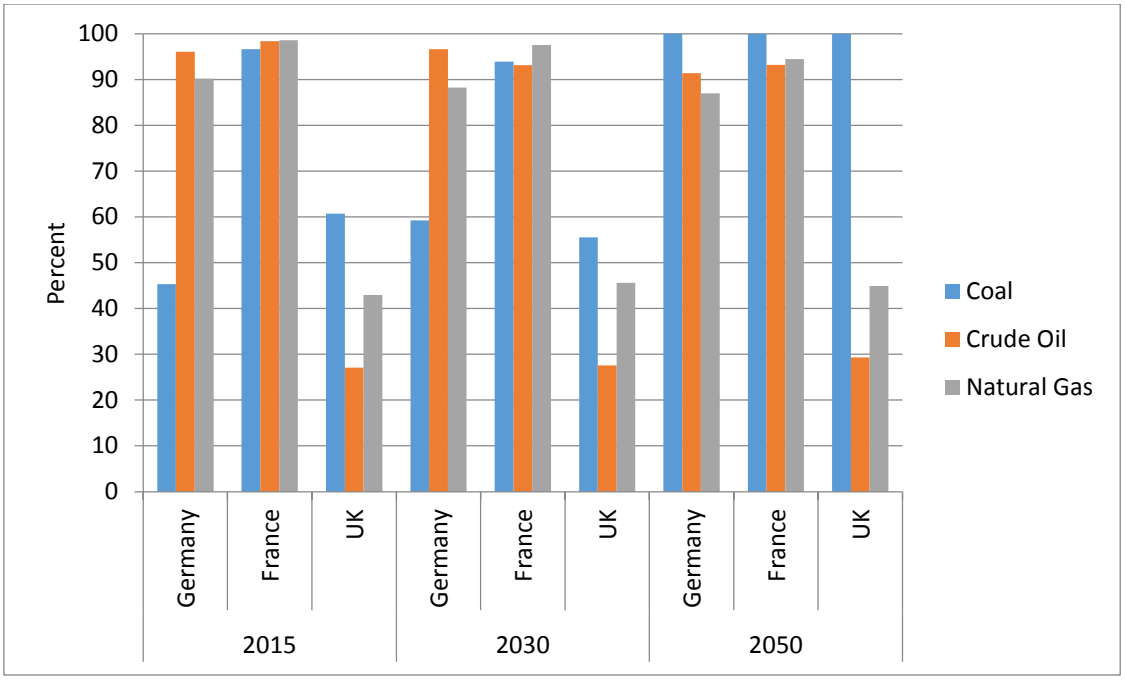

Fig. 63 Share of fossil fuel imports in primary energy consumption, 2015-2050

Natural gas is the most important resource where all the three countries are highly dependent. The import dependence of natural gas is huge in Germany and France, where Germany imported over 90% of gas in 2015 and France imported 98.5% of gas in 2015. The UK position on imported gas is better than other two countries and imported only 42% of gas in 2015. The net import dependence of gas in the UK decreases in 2030 and 2050 due to the increase in renewable energy resources and export of domestic resources.

4.2.4 Climate change mitigation - CO_2 emissions reduction

The 2030 and 2050 scenario results show that Germany, France and the UK meet their decarbonsiation targets in 2030 and 2050 through reduction in CO_2 emissions. Germany reduces the CO_2 emissions by 55% and 80% in 2030 and 2050, respectively compared to 1990 levels. CO_2 emission from fossil fuels amounted to 561 $MtCO_2$ in 1990 and decreased to 425.7 MtCO2 in 2015, representing 25% reduction relative to 1990. This emission reduces significantly in 2030 and 2050 to 251$MtCO_2$ and 111 $MtCO_2$, respectively, representing 55% and 80% reduction compared to 1990.

France reduces the CO_2 emissions to 45% and 75% in 2030 and 2050, respectively compared to 1990 levels. In 1990, CO_2 emission from fossil fuels were hovering at 305 $MtCO_2$ which were reduced to 279 $MtCO_2$ in 2015, representing a slight drop of 9% relative to 1990 levels. However, CO_2 emission reduces significantly to 167 $MtCO_2$ in 2030, representing 45% decline in emissions. The CO_2 emission further reduces to 75.3 MtCO2, representing 75% decrease in emissions.

The UK CO_2 emission decreases by 50% and 80% below the1990 level in 2030 and 2050, respectively. The carbon emissions in 1990 totaled at 305 $MtCO_2$ and decreased to 262 $MtCO_2$ in 2015, which represented 19% of reduction. The CO2 emission significantly reduces to 157 $MtCO_2$ and 63 $MtCO_2$ in 2030 and 2050, respectively.

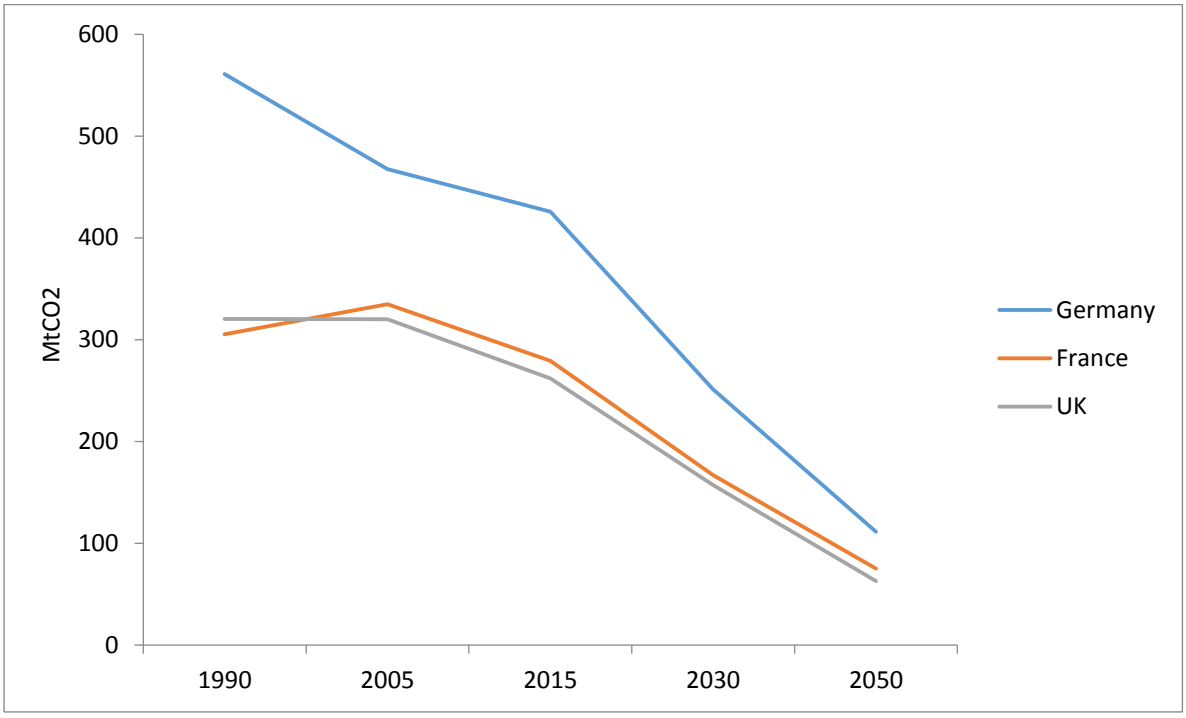

Fig.64 Total CO2 emissions, 1990-2050

Sectoral CO_2 emissions

In all major sectors, the transport sector is the largest source of CO_2 emissions followed by buildings and industry in these three countries. In transport sector, they depend heavily on oil products which has high CO_2 emission factor. It underlines the fact that in the future, it is necessary to reduce the use of oil or switch to other fuels in the transport sector in order to achieve the decarboniation targets. Considering

this, there will be a significant decline in oil consumption in 2030 and 2050. France and the UK generated almost same amount of CO_2 emissions in the range of 118-122 $MtCO_2$ in 2015, which decreases between 59-62 $MtCO_2$ in 2030, and which further reduces significantly to 9 $MtCO_2$ in 2050. This is all because both the countries took a smart step through switching from oil to biofuel and electric vehicles. Germany generated the highest amount of CO_2 emissions in the transportation sector reaching 158 $MtCO_2$ in 2015. However, due to technological innovation and fuel switching of fossil fuels, CO_2 emission declines to 17 $MtCO_2$ in 2050.

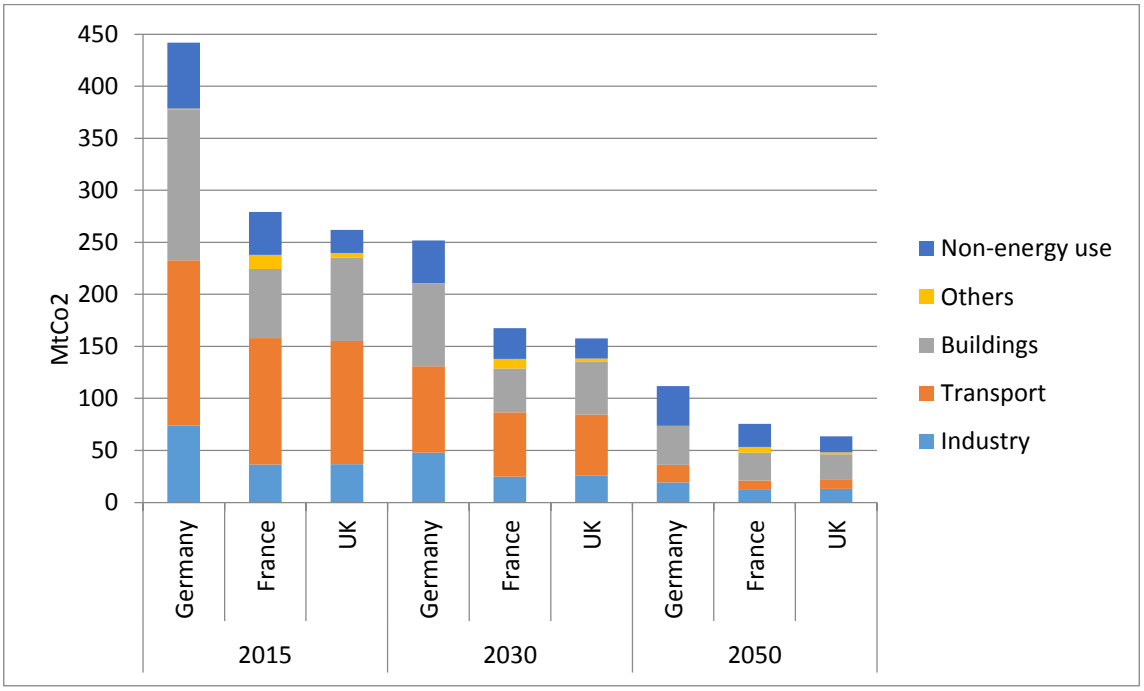

Fig.65 CO2 emissions by sector, 2015-2050

CO2 emisions from building sector falls almost to 4-fold in Germany in 2050 compared to 2015. In 2015, CO_2 emissions amouted to 145 $MtCO_2$, which significantly reduces to 79 $MtCO_2$ and 37.4 $MtCO_2$ in 2030 and 2050, respectively. On the contrary, France and the UK generated less CO_2 emissions, which accounted to less than 80$MtCO_2$ in 2015. France and the UK's building sector CO_2 emissions were 66 $MtCO_2$ and 80 $MtCO_2$, which were almost half of the Germany's building CO_2 emisisons. In 2050, France and the UK reduces the building CO2 emissios to 27 $MtCO_2$ and 24 $MtCO_2$, respectively. The decarbonisation in the building sector is therefore becomes possible due to adoption and implementation of building energy efficiency codes and standards in these countries.

4.2.5 Renewables in electricity generation

Renewable growth in electricity generation is not only a major pillar for electricity transition but also for energy transition. Integration of renewables in the electricity mix and the increase of RES in electricity generation play an important role to achieve decarbonisation targets in 2030 and 2050. In these countries, over 40% of the total CO_2 emission reduction in 2050 is due to generating electricity from renewable energy sources.

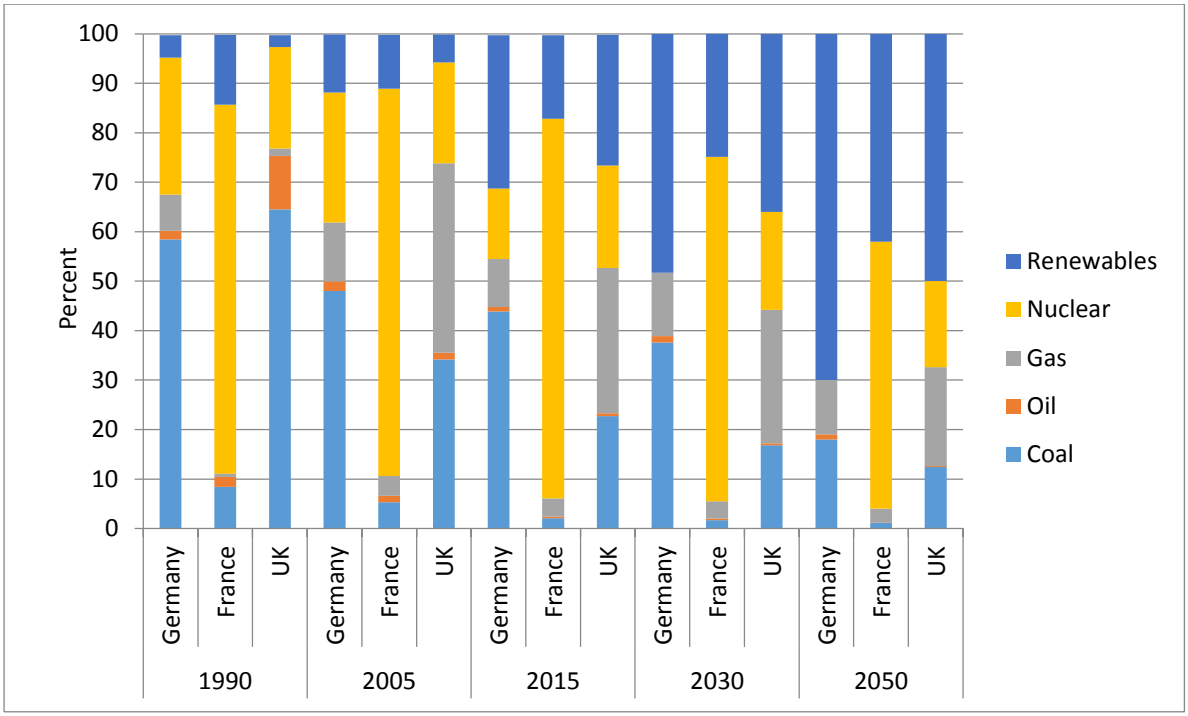

Fig.66 Electricity generation by fuel, 1990-2050

RES makes a significant penetration in the electricity mix of these countries. The 2030 and 2050 scenario shows the increasing share of renewables in the electricity generation relative to the base year 2015. The results show that fossil fuels gradually decreases in coming years, while there is a substantial growth of renewable share in electricity generation. For example, in Germany, the share of RES goes up to 48% in 2030, and this share reaches 70% in 2050, reflecting its role in decarbonization of the power generation. In three countries, the maximum growth of RES share in Germany is driven by the phase-out of nuclear power in 2022, because Germany

was left with only RES option to generate clean power. In contrast, France achieves the decarbonisation targets with a 54% nuclear share in power generation in 2050, whilst the remaining 42% comes from the renewable energy sources. The UK also manages to touch 50% share of RES in electricity generation in 2050 compared to 26% share in 2015, which is almost double of 2015. The remaining fuel share in electricity generation comes from natural gas (20%) followed by nuclear (17.4%) and coal (12.4%).

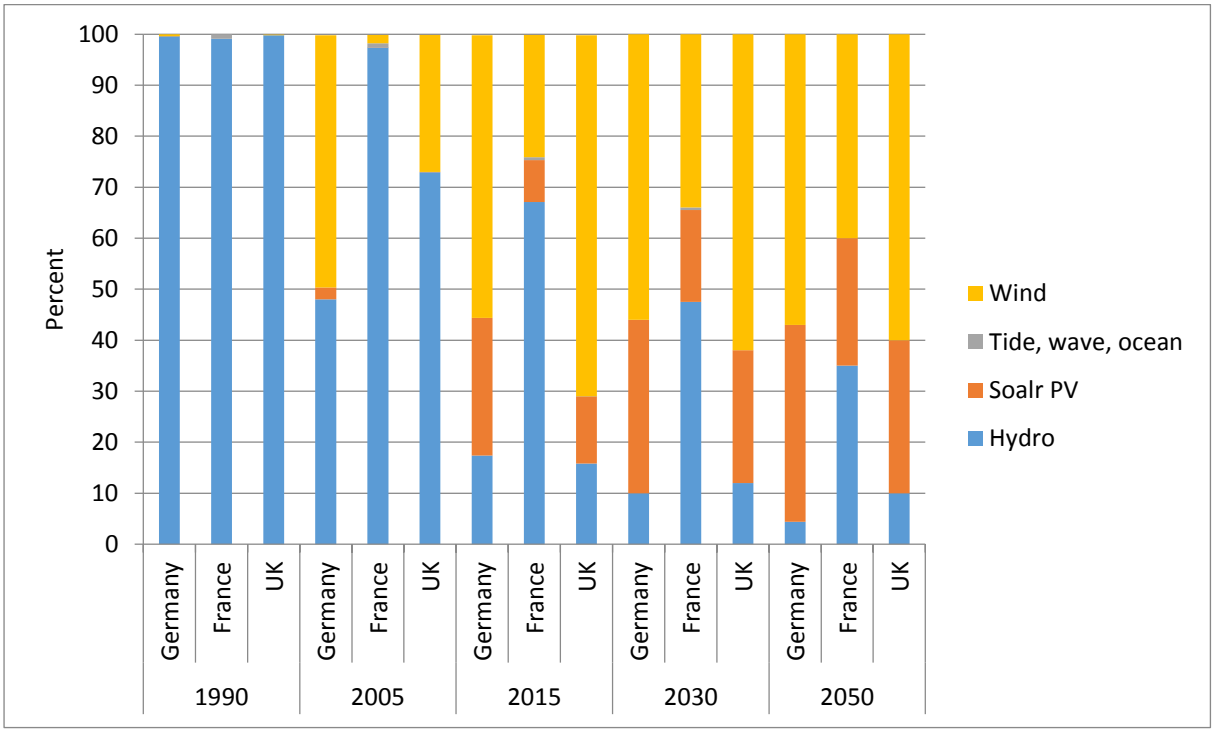

Fig.67 Electricity generation from renewables by source, 1990-2050

Fig. 67 provides a breakdown of electricity generation from renewables by source. In Germany, France and the UK, contributions from renewable technologies including hydro, solar PV, tide and wind have been increased. The solar PV and wind gained momentum in the electricity sector and contributed the highest share of electricity generation with renewables. In Germany, wind power accounts over 50% of electricity generation in 2030 and 2050, whereas in the United Kingdom, share of wind reaches over 60% of power generation in 2030 and 2050. Wind power with

renewables is the highest in the UK with a 62% share of wind. In France, the wind share accounts for 34% and 40% of power generation in 2030 and 2050, respectively. Solar PV share in power generation also increases in 2030 and 2050, where Germany's solar PV share reaches 38% in 2050, which is the highest in three countries. France also increases the share of Solar PV in 2050, which is one-fourth of power generation, while the UK's solar PV share in the electricity generation is below one-third in 2050. The remaining electricity is generated from hydro in these countries, but its contribution has been continuously decreasing since 2015. In Germany and the UK, hydroelectric power generation shares 4.5% and 10%, respectively in 2050, while France's hydroelectricity shares 35% in 2050, which is the maximum in these three countries.

CHAPTER 5

SUMMARY, CONCLUSIONS & RECOMMENDATIONS

5.1 Summary and discussion

This section contains a summary of key findings in relation to the analysis conducted in the thesis. The five elements associated with the energy policy including energy supply, energy demand, CO2 emissions, security of supply, and renewables in electricity generation have been summarized and discussed.

5.1.1 Energy supply side

In three countries, decarbonisation in energy supply was required for the achievement of low carbon energy system by 2050. Eventually, it has become possible due to combination of three low carbon energy supply solutions i.e. switching fuels, CCS technology and Renewable energy sources (RES). The first solution relies on a shift from high carbon-intensive fuel to less carbon-intensive fuel. In Germany, share of fossil fuels in the total primary energy supply shrinks from 78% to 65% in 2030 and 36% in 2050 compared to 2015. France also reduces the fossil fuel share from 45% to 35% by 2030 and 23% by 2050 relative to 2015. The United Kingdom reduces the fossil fuel share from 82% to 56% by 2050 compared to 2015. In the UK, about 60% of the contribution came from the natural gas in the share of fossil fuels, which has low CO2 emission factor. Natural gas will continue to be a preferred fuel in the UK's energy supply mix due to the abundant gas reserves in its territory. Besides gas, the most significant change in the energy supply seen by the three countries as a coal phase-out. The results of the scenario show that oil surpassed coal in 2030, and then natural gas surpassed oil in 2050 in the energy mix of these countries.

Second, all these countries include the carbon, capture and storage (CCS) technology in their fossil fuel share which helps to reduce emissions. It also plays an important role in the end-use sectors, particularly industry and power sectors. Third, all three countries increases the renewable energy sources in their energy mix.

Germany expands the share of renewable energy resources from 14% to 35% in 2030 and 64% in 2050 compared to 2015. After the phase-out of nuclear, Germany invests more in RES which can be seen through the sharp rise in the share of renewables in energy supply mix. France also increases the share of renewable from 10% to 15% in 2030 and 27% by 2050 compared to 2015. France increases the nuclear share to 50% in their energy supply mix. The UK also increases its renewable share from 8% to 27% in 2050 compared to 2015.

5.1.2 Energy demand side

The final energy demand depends primarily on the pattern of energy usage in various end-use sectors. Energy efficiency, technology and electrification are key pillars for reducing final energy demand. Germany, France and the UK reduce their final energy consumption by 2030 and 2050 compared to 2015. Building sector will continue to be the dominant end-use sector followed by transport and industry sector in 2030 and 2050.

The electrification and increasing energy efficiency of end-use sectors helps in reducing overall energy demand. Electrification in the building sector helps to reduce energy demand due to the reduction in electricity consumption of domestic appliances including lighting and kitchen appliances. It is also assumed that existing buildings will be renovated and all new buildings will be low-carbon or zero-energy buildings. As a result, space heating requirements has reduced, which in turn, reduces the final energy demand of buildings. Increasing energy efficiency in the buildings, particularly heat pumps and lighting also helps to reduce the electricity demand, thereby decreases the energy demand. Moreover, improving vehicle efficiency in transport sector through the advancement of engines and technical improvements decreases the energy demand in 2030 and 2050. In addition, technology advancements in buildings including LED lights, smart meters and sensors; and CCS technology in the industry also helps in reducing the total final energy consumption.

5.1.3 Energy security – Security of supply

The energy security of a country can be determined through its dependence on fossil fuel import. It can also be addressed through the availability of domestic resources. As the fossil fuel resources are depleting, energy security of a country can be ensured through the expansion of renewable energy sources. Therefore, all three countries expand the renewable energy sources to improve its security of supply. As a result, in 2050, the fossil fuel import dependence declines by 52% in Germany, while France and the UK reduce the import dependence by 56% and 35%, respectively.

All three countries are highly dependent on oil to meet their energy requirements, particularly in the transportation sector. Germany imported over 95% of crude oil in 2015, which reduces to 38% in 2030 and 72% in 2050. In the same way, France and the UK reduce their oil import by 70% and 52%, respectively in 2050 compared to 2015. The import dependence on other fossil fuels i.e. coal and natural gas also decreases by 2050. The increase in renewable energy sources solves the issue of energy security to a large extent.

5.1.4 Climate change mitigation – CO2 emissions reduction

Germany, France and the UK successfully achieved their respective decarbonisation targets in 2030 and 2050. Electricity sector played a prominent role in achieving their targets. Low carbon energy technologies including nuclear, RES and CCS were used in the electricity generation, thereby helping to reduce the CO2 emissions. Electrification of end-use sectors, particularly the transport sector also played an important role in reducing CO2 emissions. In 2015, the transport sector was highly dependent on oil products to meet their needs. However, in 2050, over 60% of the internal combustion engine vehicles switch to electric vehicles and hydrogen vehicles. The consumption of oil in transport also reduces and also replaced by biofuels.

5.1.5 Renewables in electricity generation

Renewables played a key role in CO2 emission reduction. In all three countries, in 2050, more than 40% of the CO2 emission reduction is due to renewables in electricity production. All these countries increased the share of renewable energy sources in electricity generation. Germany increases the RES share to 70% by 2050, while France and the UK increases by 42% and 50%, respectively. Out of all the renewables, wind has contributed most to the electricity generation, where in Germany, 54% of the electricity generated from wind renewable, while France and the UK generated 60% and 40% of the electricity from wind renewables. Electricity is continuously declining from hydro in Germany and the UK, where they generated less than 10% of the electricity by 2050. In contrast, France generated 35% of the electricity from hydro in 2050.

5.2 Conclusion

The study has shown that it is feasible to achieve the decarbonisation targets of Germany, France and the UK by 2030 and 2050. All the three countries successfully transition to a low carbon economy by 2050. The energy transition in Europe's largest economies can also be a driving force for a global energy transition, particularly for European Union (EU) energy transition. In addition to decarbonisation, the energy transition of these countries was also based upon energy independence and fossil fuel reduction. The study examined a range of energy policy areas (energy supply, energy demand, energy security, climate change mitigation and renewables in electricity generation) associated with decarbonisation targets with the primary goal of achieving secure and climate-friendly energy system. The reduction in CO2 emission has been achieved through a large transition in the energy supply mix, electricity mix, and energy demand in all the end-sectors. Average 65% of the energy supply mix made up from low carbon sources in 2050

A combination of RES, energy efficiency, electrification and low-carbon technology in the energy system enables the successful transition to a low carbon economy. Efficiency plays a major role in addressing all the elements of energy trilemma; RES

ensures reduction of CO2 emissions along with reduction in fossil fuel import dependence; electrification and low-carbon technology make significant contribution in reducing CO2 emissions. The energy transition in demand sectors are mostly made up from three main sectors – electricity, buildings and transport, where the achievement of its decarbonisation objectives relies on three pillars - Fuel switching, electrification and energy efficiency. For example, electrification of the transport sector in which internal combustion engine vehicles are replaced by electric vehicles; fuel switching on renewables from coal to generate electricity; and energy efficiency contributed the most in building sector to reduce the energy demand.

Germany, France and the UK took the lead to facilitate the energy transition process through the establishment of energy transition plans, where ambitious long term decarbonisation targets have been set. For Germany and the UK it is CO2 emission reduction of at least 80%, while for France it is at 75%, compared to 1990. In addition, these countries improved their security of supply through the expansion of renewables and reduce the fossil fuel import dependence. These countries are also pioneers in the development of low carbon technology, where Germany took the lead in hydrogen and fuel cell technology while France contributed through nuclear power technology.

Germany adopted the energy transition plan, which is known as “Energiewende” The expansion of renewables, nuclear power plant phase-out, and 80%-95% reduction of CO2 emissions by 2050 are key elements of German Energiewende. Germany phase-out the nuclear power plants by 2022 and coal-fired plants by 2038. Due to phase-out of nuclear power and coal-phase out, energy security problems started to rise, which has been solved by the increase of renewables in the electricity mix by 2050. Renewable has become the main source of electricity generation in 2050. Germany expanded renewable energy sources by 70% in 2050. Solar PV and on-shore wind power have become more competitive to generate electricity among renewable energy sources. In 2050, most of the oil is replaced by bio-fuels for transportation use. Internal combustion engine vehicles are also replaced by Electric vehicles. Energy efficiency target has also been achieved through a reduction of 50% in final energy consumption by 2050 compared to 2008. All these measures have contributed to the success of transition towards a low carbon economy.

France adopted the 'Energy Transition for Green Growth' law in 2015 with a long–term decarbonisation targets in 2050. The French government was uncertain about the share of nuclear power in the electricity mix. However, they decided to reduce the nuclear power share in the electricity generation by 50% from 75% by 2025. The scenario study shows that France increases the nuclear share in the energy mix up to 50% and renewables by 27% in 2050. However, the share of renewables is much lower than that of Germany, which is compensated by other clean fuel i.e. nuclear energy. The combination of clean energies including nuclear energy, hydropower and renewable energy made a large contribution towards energy independence, which reduces the dependence on the import of fossil fuels. France also achieved the energy efficiency target by 2050 through reducing the final energy consumption by 50% compared to 2012.

The United Kingdom established the Climate Change Act in 2008 and sets a target of 80% GHG emission reduction in 2050 compared to 1990. Climate change was the dominant issue when Climate Change Act was introduced in 2008. However, it was later modified with the inclusion of energy security issue. In recent years, the UK energy transition plan has gradually strengthened and is moving towards the transformation in which all the elements of energy trilemma have given equal importance. Natural gas and renewables are the main ingredients of the UK's energy supply mix in 2050, where both contributed 32% in the energy supply mix. The Renewable Energy Strategy was adopted in 2009 to promote renewable energy. Besides this, several renewable schemes were introduced including Renewables Obligation (RO), Contracts for Difference (CfDs) and Feed-in-Tariff with the aim of generating electricity from renewable sources.

5.3 Recommendations

This section provides key recommendations aimed at low carbon energy system in 2030 and 2050.

- Energy transition and decarbonisation plans need to be implemented swiftly in all the sectors in order to keep the 2^{o}C target alive. This implementation is paramount for electricity sector and transport sector as these sectors are

highly dependent on fossil fuels. The delays in decarbonisation of these two sectors would further delay the transition towards a low carbon future.

- Expansion and deployment of Renewable energy sources, especially for Germany as it will be the only clean energy option after phasing-out nuclear power plants in 2022. Biomass, solar PV and onshore wind are three main renewable energy sources that have potential to replace fossil fuels and meet the energy demand in all the sectors. Renewable power including onshore wind, hydropower and solar PV is crucial for decarbonising the electricity sector. Renewables also ensures the security of supply and reduces dependence on fossil fuel import.
- Scaling up deployment of low carbon technologies in different sectors. Technology and innovation helps in demand reduction as well as CO2 emission reduction. Therefore, a number of renewables and other emerging technologies need to be considered including CCS technology for industry and power sector; smart grids; smart meters and heat pumps for building sector; smart technologies including automation and sensors for building sectors; hydrogen for heat, power and transport sector; fuel cells and battery electric technology for transport sector; etc.
- Energy efficiency needs to be included in all end-use sectors. Energy efficiency is considered as key pillar of energy transition and decarbonisation, which helps in meeting the targets rapidly and profitably. Energy efficiency has much potential in building and transport sectors where energy efficiency measures could save a lot of energy, improve the energy performance and reduce energy demand.
- Electrification of end-use sectors can be considered as the major option for decarbonising the energy system through the low-carbon electricity supply. Electricity can replace the use of oil and gas in the buildings and transport sector, where electricity displaces the gas for the use of heat in buildings, while electric vehicles displaces the internal combustion engine vehicles.

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