Germany 2030: Estimation of the Impact of Electrification of Individual Road Transportation Sector in the Economy

An Exergy Economic Analysis

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Abstract

Technological progress is driving the growth of economic output. Technological progress is a source of energy transformation. The connection between the final energy use of Germany (measured in exergy metrics) and GDP – called the overall thermodynamic efficiency of the German economy, was examined in order to explain economic development itself. The goal of this work was to link the exergy efficiency with technological progress to model the upcoming technological change in the individual road transportation sector. The technological change within this sector was analysed regarding its impact on the future development of the economic output until 2030. The neoclassical macroeconomic model is taken as a base for calculation. The total factor productivity is explained by the measure of exergy efficiency.

One of the main conclusions form this work is that the aggregate energy efficiency can be used to explain the total factor productivity of Germany from 1990 onwards. This link, obtained by the analysis of historical data, was used to derive scenarios for the future development for 2030. The scenarios allowed to conclude that the electrification of the individual road transportation sector contributes to an increase in final to useful aggregate energy efficiency of the economy. The increase in final to useful aggregate energy efficiency leads to an increase of total factor productivity which means an increase in economic output when a constant contribution of capital and labour is assumed. Thus, electrification of the individual road transportation sector can have a significant contribution to the future economic growth rates in Germany.

Keywords: Exergy, Useful Work, Exergy Economics, Individual Road Transportation Sector, Scenario Planning, Germany 2030

Resumo

O progresso tecnológico está a alavancar o crescimento económico. Este progresso tecnológico é uma fonte de transformação energética. A ligação entre a energia final total alemã (medida em unidades de exergia) e o PIB alemão – ou seja, a eficiência exergética geral da economia alemã, foi analisada com o objetivo de explicar a evolução da própria economia alemã. Para esta análise, o objetivo deste trabalho foi o de ligar a eficiência exergética ao progresso tecnológico para modelar a mudança tecnológica no setor de transporte rodoviário individual. Esta análise foi aplicada ao presente e foi estimada a evolução futura até 2030, usando o modelo macroeconómico neoclássico como base de cálculo e onde a produtividade total de factores é entendida como a medida de eficiência exergética.

Este trabalho permitiu concluir que a eficiência exergética pode ser usada para explicar a produtividade total dos fatores da Alemanha a partir de 1990. Esta ligação obtida por dados históricos foi então utilizada para derivar cenários para a Alemanha para 2030. Pode-se verificar que a eletrificação do setor de transporte rodoviário individual contribui para o aumento da eficiência energética agregada (de energia final para útil). Este aumento traduz-se num aumento da produtividade total dos factores, o que significa um aumento do PIB quando se assume uma contribuição constante do capital e do trabalho. Assim, a eletrificação do setor de transporte rodoviário individual pode ter uma contribuição significativa para as taxas de crescimento económico futuro da Alemanha.

Palavras-chave: exergia, exergia útil, economia energética, setor de transporte rodoviário individual, Alemanha 2030

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Acronyms

A residual in the Cobb-Douglas function.

B exergy.

E energy.

E_F final energy.

E_P primary energy.

K capital.

L labour.

N_e number of employed people.

N_p population.

Q economic output.

S aggregate efficiency value.

TP labour force participation rate.

U useful work.

α capital share.

β labour share.

δ depreciation rate.

η first law efficiency.

ϕ exergy factor.

ε second law efficiency.

a residual index.

h annual hours worked per person.

i energy carrier.

j economic sector.

k capital index.

l labour index.

m exergy end use category.

q economic output index.

r investment capacity.

s aggregate efficiency index.

t year.

td unemployment rate.

ADF Augmented Dickey-Fuller Test.

DAX German Stock Index.

EFF aggregate efficiency.

FRG Federal Republic of Germany.

GDP gross domestic product.

GDR German Democratic Republic.

GHG greenhouse gases.

HCI human capital index.

IEA International Energy Agency.

PWT 9.0 Penn World Table 9.0.

TFP total factor productivity.

VAR vector autoregression.

Chapter 1

Introduction

1.1 Motivation

Throughout the world the issue of climate change is extensively discussed. International agreements have been signed in order to fight global warming. The most recent one was signed in Paris in 2015 to agree on the compliance of the two degree Celsius limit for the increase in global annual average temperature. Countries in Europe put a lot of effort in finding solutions to reduce the emissions of greenhouse gases (GHG) that drive the increase in global annual average temperature.

However, besides the environmental aspects, economic ones play a significant role in discussions on the trend to follow within a country. To ensure wealth for the citizen, a strong economy needs to be ensured. The intended growth path is an increase in economic output while avoiding negative effects on the environment. The major impact on the environment occurs due to the use of fossil fuels as energy carrier.

Within the industrialisation process, energy played an important role in order to increase the productivity through either supporting or replacing human labour. During the first industrialisation process in the 19th century, coal was the main energy carrier used to run machines and increase the availability of mechanical work. A variety of energy carriers has been made usable during this time. Mechanical work has been made available on small scale by combustion engines. Later, the development was dominated by information technologies and automation. Today, the industrialisation process goes along with topics related to digitalisation which impacts economies, industries and human beings. It addresses topics like Artificial Intelligence, robotics, Internet of Things, etc.

The industrialisation process shows that energy and economics are closely related to each other. Looking at the crude oil prices and the economic growth rates in Germany reveals that increases in prices were followed by a reduced growth rate. This connection leads to the need of understanding how the economy is affected by a change of energy demand and supply.

Germany began with the energy transition, which is the process of turning from the use of conventional energy carriers to renewable energy sources. In year 2011, Germany's government decided on the nuclear phaseout by 2022. The share of renewable energy carriers is successively increased in the energy supply.

Conventional and renewable energy carriers complement one another and make energy available on every scale level. The development needs to follow a way that ensures both economic growth and being able to reach the climate goals.

Therefore, the use of energy carriers needs to be evaluated regarding the effect on economy. The goal needs to be a prospering economy with the commitment of minimising a negative impact of the economic activity on the environment.

Policies target the development of technologies to accelerate and concentrate the efforts taken to reach the goals. The policy design is based on models that allow a statement to be made about the impact of the technological change on the economy. In order to define polices that guide the technological development towards a future of economic growth economic models are necessary that evaluate the technological change in regard to their impact on the economy. The technological development is closely linked to an electrification of economic sectors in Germany.

The automotive industry is the industry with the highest business volume in Germany. Within the manufacturing sector it contributes to almost 20 % of the gross value added. In the coming years it will face a major change regarding the technology used.

The diesel scandal revealed the use of cheat software in diesel cars which was illegally implemented to pass the emission tests in the standardised test cycle. The results on the road deviated strongly from the lab results for some car models of several German brands. That directed the focus increasingly on the local air pollution by cars in city regions and on global scale.

Policies target the support of environmentally friendly technology. It is important that policies take the influence of that technological change into consideration in order to ensure a positive impact on the economy.

An answer on the question is required how policies guide the way to the future of the transportation sector without neglecting the major industry - the automotive industry.

In order to evaluate both economic growth and the energy demand of an economy, the economic growth model has to be extended by the aspect of energy. The neoclassical economic growth model does not consider an energetic measure. However, from the thermodynamic point of view, the measure of energy needs to be considered in a critical way, due to the fact that energy cannot be consumed, only transformed. Thus, in the following the exergy metric is considered in order to describe energy flows. Exergy is used as a measure to describe the availability of energy to perform thermodynamic work. It is considered as a measure for the quality of energy.

1.2 Scope and Goal

Due to the importance of the automotive industry in Germany and the recent technology change in the transportation, the economic growth needs to be ensured in this sector. The goal is to understand the future development of the transportation sector and how it affects the German economy. The electrification of the transportation sector will not only affect the sector itself, it will also lead to other requirements in the electricity sector. Therefore, a model is required to examine possible future pathways. The model needs to include the macroeconomic aspects capital and labour and an energy measure. It needs to be able to present the influence of technological changes on the economy. It has to consider especially the impact of a change in energy supply and energy demand on the economy. Based on the model, is to make a statement about how the energy supply and the technologies used need to change to ensure future economic growth. The intention is to provide a statement of which economic growth can be achieve when a change in technology and in energy supply happens.

The model is set up to identify the crucial parameters and provide a statement about the sensitivity of the parameters regarding changes so that it can be used as a base for decision making processes, future and strategy planning. Therefore, scenarios are developed that show the impact of decisions that are taken about the strategy and technology development and how they impact the German economy.

A suitable measure needs to be implemented to evaluate the impact of a the technological change in an economy on the economic output.

Therefore, scenarios are provided for the development of the German economy for 2030. These scenarios are based on an economic growth model that considers the aggregate efficiency which is the overall thermodynamic efficiency of the economy. The aggregate efficiency is a measure on the macroeconomic level to evaluate the conversion from the maximal possible amount of work that can be obtained by energy to the useful step of energy that provides the desired outcome.

The aggregate efficiency will be endogenised in the economic growth model and to show that the improvement of the aggregate efficiency can lead to an increase of economic output. That provides a link between the aggregate efficiency and the total factor productivity. For the economic model the exergy economic approach is used. That means exergy is considered to provide a measure for available energy that can be used by the consumer.

This thesis provides the first effort to apply this systemic exergy economic approach for the German economy with analysing the future development of the individual road transportation sector. In order to explain the economic output the increase in aggregate efficiency besides the two production factors capital and labour is examined.

In order to provide a statement about the future development, scenarios with an improvement of aggregate efficiency are modelled and show that an improvement of the aggregate efficiency of the economy leads to an increase in total factor productivity. The total factor productivity is responsible for a major share of economic output. Cultural and social changes are not considered in the model and their influence not scope of this work. So far, economic models applied for Germany considered the energy demand which was not enough to entirely explain the economic output of the country. This thesis provides the first macroeconomic application of the exergy economy model for the German economy and executing an analysis of the future development of the individual road transportation sector with this approach.

1.3 Outline

In this thesis historical data for Germany is analysed for both macroeconomic variables and energy variables. Both macroeconomic data (i. e. data for capital, labour, labour shares, hours worked, economic output) and energy data (i. e. primary energy supply and final energy demand) is collected from international and national data bases. The neoclassic macroeconomic growth model is applied for Germany. It is pointed out, that there is a lack of explanation for the gap between economic growth and capital and labour growth. In literature, the gap is called technological progress.

The energy data is examined by using the exergy approach which is a way to evaluate energy according to its availability to do thermodynamic work, called useful work.

Considering the exergy economic approach, the useful work data is connected to the macroeconomic data. In this thesis the economic growth model is verified in the analysis in order to check the connection of Germany's economy with its consumption of useful work. The exergy approach is used to be able to compare different technologies that provide the same end use. Issues about the statistical verification of the correlation of the aggregate efficiency and total factor productivity are pointed out. In chapter 2 the basic background theory is described that is needed for the further process. The process is further explained in chapter 3. Additionally it is explained, how and under which aspect the data is analysed and further used for the analysis and calculation. In chapter 4 the analysis is executed and the findings are pointed out.

Based on the analysis, future scenarios are derived in order to project the development of the economy and the use of useful energy to the future. Chapter 5 shows scenarios for the following years until 2030 with future trends of the data. In chapter 6 the work is summed up and concluded. Within the scenarios, possible developments of technologies in use are shown with their effect of change in aggregate efficiency, which means a change in the amount of final exergy that is necessary to provide the desired useful work. The next step considers the development of primary energy input.

Based on the neoclassical economic growth model from SOLOW and SWAN, efforts were taken to extend the economic growth model, that includes capital and labour as factors of production. The extension of the model was usually done with adding the physical, the thermodynamic aspect into the economic approach. Some authors included energy and material into the economic model.

The economic growth model that includes besides the neoclassical factors of production, capital and labour, the measure of useful work is applied for Germany. It is checked, how the trend of economic growth, measured in GDP and the trend of useful work consumption is developing over time by showing the useful work intensity of German economy. The useful work consumption of end use categories is as well examined as the one of the sectors. A statistical analysis has been executed in order to check a statistical correlation between the technical progress and the aggregate efficiency of the economy. After showing, that the model can be used for Germany, it is applied in order to create scenarios for the next years until 2030.

The time period considered for the future scenarios is chosen to be far enough in the future to make significant changes in technology visible, however, the time frame is in a range that ensures a reasonable reliability of the scenarios.

This thesis follows an approach that is based on the approach used in the MEET2030 project (Alvarenga et al., 2017). The MEET2030 project is a project executed in Portugal to examine historical data of the economy and of the energy demand in the country. The project provides future scenarios for Portugal in 2030 on the path to a low carbon economy and proposes opportunities for the economy to grow.

Chapter 2

Linking Energy and Economic Growth - the State of the Art

Starting from the beginning of the industrialisation process with the increase of economic activities the efforts to describe, understand and model economic activity have increased. Thus different models have been developed. The neoclassical model that was developed in the middle of the last century is still the base of the economic models used today. However, this model was not capable to explain the entire economic growth that could be observed in the economy. In order to improve the model several efforts were taken to include the factors of energy and material into the growth models. The exergy economics approach was proposed and successfully tested for a number of countries (UK, Japan, US, Austria, Portugal). The exergy measure allows to evaluate the availability of energy to perform thermodynamic work. The concept is strongly linked to thermodynamics. In section 2.1 the development of economic theory is described. Several thermodynamic expressions are defined in section 2.2. Then, the approaches to explain economic processes with thermodynamics are described in section 2.3.

2.1 Economic Growth Theory

The beginnings of modern economic theory started with the classical economics in the 18th century when the first efforts were taken to understand, describe and model economic interrelations.

In classical economics the principle of a free market has been phrased by Adam Smith. In his book ”The Wealth of Nations” the author describes the mechanisms of a market assuming each participant pursues to maximise its own benefit.

In this theory the value of a product is determined by the time and monetary effort it takes to produce it. From the second half of the 19th century onwards, the classical economic theory was replaced by the neoclassical economic theory. Karl Marx, who experienced important parts of the industrialisation, described the meaning of capital and labour as production factors.

On the macroeconomic scale, Robert Solow and Trevor Swan set up an economic growth model for long-run economic growth (Solow, 1956, 1957), (Swan, 1956). The model is considered as part of neoclassical economic theory.

It is assumed that the production of goods and services can be expressed as a function of capital and labour, which are called the two factors of production (Warr et al., 2008, p. 126). Thus, the aggregate production function can be written as (Solow, 1957):

$$Q = F(K, L; t) \tag{2.1}$$

where Q represents the output of goods and services in monetary terms and K and L the capital and labour in physical units, i. e. capital stock in recent currency and labour in total hours worked. The function is time dependent. A gap remains between the output and the two factors of production, so that a time dependent factor needs to be added to model the remaining residual. Due to the residual, the function can be rewritten to:

$$Q = A(t)f(K, L) \tag{2.2}$$

where $A(t)$ represents a time dependent multiplier that describes the residual, that is called Solow-residual. The residual is explained as technical progress or technical change. Over time the technical change causes a shift in the production function. The multiplier is a measure of the productivity, that is why it is usually called the total factor productivity (TFP). In the economic model the total factor productivity is has a major contribution to economic growth which is handled as an unexplained exogenous driver (Ayres and Warr, 2005).

SOLOW states that the desired parameter to determine the output from the function is the annual flow of capital services (Solow, 1957, p. 314), however, due to lack of available data the estimate of the stock of capital goods in existence is used. This is the less preferred measure because the production function should consider capital in use instead of capital in place. However, capital stock can be multiplied by the values of official statistics for capacity utilisation (Dreger and Schumacher, 2000, p. 8).

Labour is measured by using the total number of employed people multiplied by the average annual hours worked in order to determine the total annual hours worked. Labour can be corrected by using the human capital index as a factor to include the education level of labour force.

Due to empirical testing the use of a function in form of the Cobb-Douglas function is suggested to model the economic output in a aggregate production function (Solow, 1957).
SWAN presents the constant-elasticity function (Swan, 1956):

$$Q = A(t)K^{\alpha}L^{\beta} \tag{2.3}$$

with $\alpha + \beta = 1$ and α and β are the output elasticities for capital and labour. These two parameter model the impact of a change of output when changing a factor of production by a certain amount.
With Equation 2.3 the TFP can be calculated.

As a measure for economic output the gross domestic product (GDP) is used. It is a common measure to determine economic power and economic growth of a country.

The approach taken here regarding the useful work, provides an aggregate consideration of the sectors and end uses. GDP is defined as the total value of all final goods and services produced within the boarders of a country.

It does not account the ownership. However, countries with high GDP per capita are considered as rich ones. Furthermore, the measure does not include environmental destruction. That can be both the pollution of the environment and the depletion of natural assets (e. g. forests, fisheries or mineral deposits, etc.). Especially in countries that depend on oil exports, fishing grounds, forests or mines the measure does completely neglect the sustainability in the long run (Ayres and Warr, 2009, p. 303).

The extent to which it is disaggregated does not reach far enough to make it necessary to take a different measure of economy than GDP.

The use of gross domestic product as a measure for economic growth is controversially discussed Ayres and Warr (2009).

Technological knowledge is embodied in labour and included into the production function (Uzawa, 1961). The fact of improvement of labour efficiency is linked with the ratio of labour employed in the educational sector.

A two-sector model of economic growth is set up. The investment good sector is as well considered as the consumption good sector.

Based on Marx' "Das Kapital", UZAWA developed the two-sector growth model. It is the effort to put Marx' ideas into a more complete and analytical term. Marx' view on economy is based on the assumption that it consists of capitalists and laborers. Whereas in neoclassical economics the participants are considered as individuals which behave as *homo economicus* that implies a rational and self-interested behaviour. After the two-sector model, UZAWA wrote an aggregate model, that considers technological progress as endogenous. That goes along with the idea of SOLOW'S model as he considers technological progress as an endogenous factor.

A real economic system depends on physical material and energy inputs. That is why GEORGENSCU-ROEGEN points out, that both standard and Marxist economists ignore the problem of natural resources. He is the first one who points out, that there is more to economics than an equilibrium steady state that will every time return to equilibrium after an unexpected event.

The importance of thermodynamic processes is pointed out, since every process leads to an increase in entropy. Every transformation of materials needs exergy and will create entropy. Due to the second law of thermodynamics, no recycling process will bring back the total amount of materials to the initial state. Materials can be recycled, but not to 100 %, due to the second law of thermodynamics. Over time it will be more and more exergy intense to extract a material. Scarce materials are getting harder to extract so that recycling will become energetically more intense over time but it never becomes impossible.

The earth as a thermodynamic system is only open to the energy flow of the sun. Matter from space is negligible because it is already dissipated (Georgescu-Roegen, 1975).

Materials play a significant role in economy which is neglected by neoclassical economic theory.

2.2 Thermodynamic Definitions

The measure energy is defined as the capacity to do work (Grubler et al., 2012). Since energy can neither be created nor destroyed, it can be only transformed to different forms (Wall, 1977). The most important forms are electric energy, chemical energy, kinetic energy, thermal energy, potential energy and electromagnetic energy.

For the following process several terms are defined which are used to differentiate between the stages in energy flows from the primary stage to the useful stage where the energy is used for the desired purpose.

Primary energy is embodied in natural resources in different forms of energy. I. e. as potential energy in water reservoirs, chemical energy in coal, oil and gas, as electromagnetic energy in solar radiation and in nuclear reactions. To make use of the primary energy sources, energy is transformed into other stages of energy. Depending on the form of primary energy, the energy is transformed into secondary energy, i. e. electricity, gasoline, jet fuel or heating oil, which ensures the usability of the energy.

The stage of energy which is delivered to the end user is called the final energy. It is transformed in

the end user's device to useful energy. Useful energy provides the energy service that the end user desires and that fulfils the end user's needs. An energy service can be e. g. mobility in shape of moving a vehicle, thermal comfort due to a warm room, illumination through light, communication, information, etc. (Grubler et al., 2012). When using this form of energy, the energy is dissipated while using it.
The steps of an energy flow are shown in Figure 2.1. Between each step of the energy flow, the transformation process leads to losses in shape of heat losses. The energy losses do not imply that the energy disappears, it is rather transformed into a not desired energy form so that it cannot be used for the desired purpose. The share of energy that is transformed into the desired energy form, is given with the first law efficiency (η), whereas the losses are given with the remaining share ($1-\eta$).

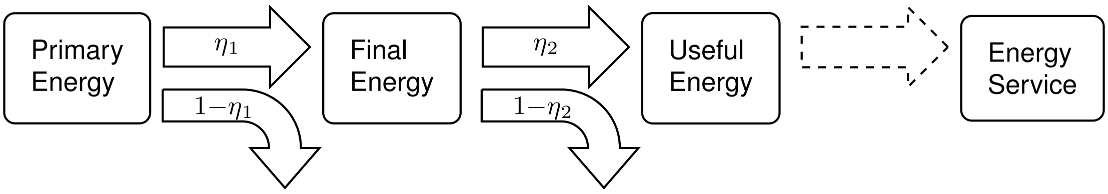

Figure 2.1: Energy Flow adopted from Serrenho et al. (2016)

Giving an example, chemical energy embodied in the primary energy source coal is transformed into thermal energy in a power plant to heat up the water cycle in the system. The produced water vapour transforms its thermal energy to kinetic energy in a turbine. The kinetic energy of the turbine is transformed in a generator into electrical energy which is transmitted to the end user. The electricity is the final energy that is used by the end user to transform it to useful energy which can be, depending on the service, for example kinetic energy, electromagnetic energy, etc.
At every step of energy transformation a certain share of the energy is transformed into thermal energy that cannot be used for the actual purpose.

However, the measure of energy for a system does neither state to which extend the energy can be used to provide the desired energy service nor which amount can be used to perform work. Considering this fact, a different measure is needed in order to make a statement of the availability of energy.

A possible way to evaluate the energy flow is using exergy as a measure of which share of the energy can be completely converted into other useful forms of energy. Exergy is the measure of available energy, that is energy capable of performing mechanical, chemical or thermal work (Ayres and Warr, 2005, p. 185). Therefore the exergy approach can be used to evaluate the quality of energy (Grubler et al., 2012). Exergy is the maximum amount of work that can theoretically be recovered from a system as it approaches equilibrium with its surroundings reversibly, which implies an infinitely slowly process. It is also a measure of distance from equilibrium (Ayres and Warr, 2009, p. 78).

Exergy is measured in energy units whereas their values are close to those of enthalpy (heating values) for all ordinary fuels (Ayres and Warr, 2005, p. 186).
In contrast to the energy, within an energy flow a share of the exergy is destroyed in each step of transformation and entropy is created. Entropy is a measure of exergy destruction. It is created during the energy conversion process.
All natural and technical processes are irreversible, which means, that the energy that is once transformed to a different form, cannot be transformed back entirely (Doering et al., 2016, p. 37).

Thus, only the quality of energy is important for the energy use and can be consumed. The quality of energy, measured by the exergy, decreases all along the way from the primary stage of natural resources

until the final desired service.
The exergy that is used to provide the energy service is called useful work. This measure gives the amount of exergy that is needed to provide the desired energy service. Looking at the energy flow at the useful stage ensures, that the differences in efficiencies are no longer considered in comparing the amount of useful work needed in different uses. The exergy flow is presented in Figure 2.2.

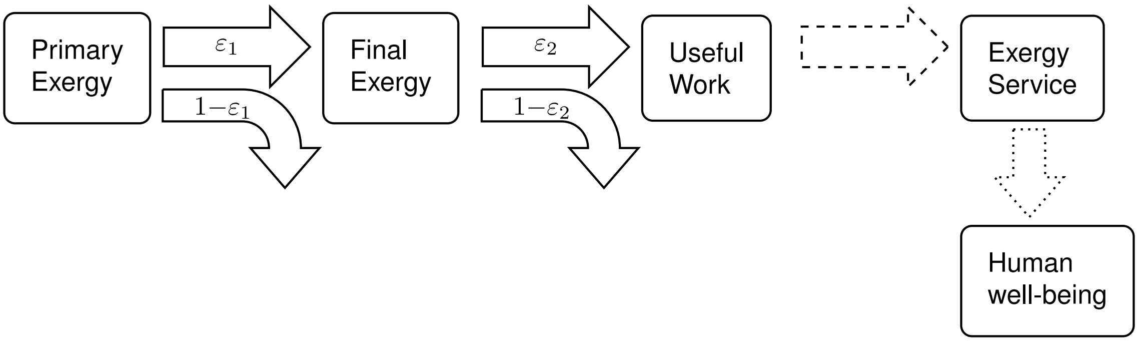

Figure 2.2: Exergy Flow adopted and extended from Serrenho et al. (2016)

For most processes a complete conversion into the desired energy form can never be reached (Doering et al., 2016).
The first and second law of thermodynamic describe these facts. The energy conservation from the first law of thermodynamic states that energy cannot be destroyed, whereas the second law makes a statement about the direction of the energy conversion (Doering et al., 2016). That means, that energy flows always from the state of higher quality to the form of lower quality, e. g. mechanical or electrical energy is transformed to internal energy. The second law of thermodynamics can also be called the principle of exergy reduction (Doering et al., 2016, p. 1).

In the transformation from final exergy to useful work the second law efficiency gives the share of exergy, that can be used for the exergy service.
Thus, the second law efficiency is calculated by the ratio of useful work and final exergy.

$$\varepsilon = \frac{\text{Useful Work}}{\text{Final Exergy}} = \frac{U}{B} \tag{2.4}$$

Where U is the useful work and B is the final exergy. The second law efficiency is specific for each end-use and the technology that is used. Apart from this disaggregated point of view, the second law efficiency can be determined for an entire economy. It is called aggregated second law efficiency (EFF).

Considering the primary stage of energy supply leads to an assessment of energy services that is not considering the efficiencies of the used technologies in order to obtain the desired service.
That leads to an over-weighted accounting of those energy services with lowest conversion efficiencies. With the change of efficiencies over the time by improvement or replacement of technologies, the weighting of the energy services varies without necessarily varying share of the energy service itself.
For example, a passenger kilometer travelled by car is accounted by the the primary energy input of crude oil. That is much higher than a passenger kilometer travelled by bicycle which primary energy input is food caloric intake.

In this thesis the exergy flow is followed up to the useful step. The aspect of what amount of useful work is required to provide human wealth is not considered as well as the question what other aspects besides useful work (e. g. shelter, etc.) are needed to reach that state.

2.3 The Exergy Approach

The relationship between economic growth and energy use is multifaceted and variable over time. The need of high-quality energy services is a necessary condition for economic growth (Grubler et al., 2012). The fact that energy cannot be completely excluded from economic growth functions is shown by the historical observation that each increase in oil prices went along with a reduced growth rate of gross domestic product (GDP). The scarcity of energy supply affected the economic output.

In the time period after the Second World War six recessions occurred in Germany (Raeth, 2009). The oil price crisis in 1973 and 1979/80 caused a drop in GDP in most countries. These are further described in section 4.1. Shown on this example of contemporaneous occurrence of oil price increase and GDP decrease makes it reasonable to assume that some kind of correlation exists between energy and economy. Due to a two-directional relationship economic growth increases the demand for energy services and the corresponding upstream energy conversion and resource use (Grubler et al., 2012, p. 114).

Ayres and Warr (2009) find that the model used in neoclassical economics is able to explain a small fraction of the observed growth. The neoclassical economic model considers capital and labour as factors of production because both are indispensable for the production process.

However, a real economic system depends in addition to those two input factors on physical material and energy inputs. Therefore, energy and materials can be considered as factors of production with the same reason as capital and labour. Nothing can be produced without transformation of natural materials and consumption of exergy and production of entropy (Ayres et al., 2003).

Thus, the energetic measure is included into the economic growth model as a third factor in order to explain the gap to the real economic growth (Warr et al., 2008).

Energy demand and resource consumption within an economy is both a driver of growth and a consequence of growth. The authors attempt to characterise an economy by primary physical properties, i. e. mass and exergy conversion. Further they assume that consumption of natural resources and especially exergy is an important factor of production and a driver of economic growth. Exergy is considered as an independent factor of production, the third factor of production, along with capital and labour (Ayres and Warr, 2009, p. xx).

The difference of capital and labour as production factor in comparison to exergy is that capital and labour are not consumed in the production process, whereas exergy is. A time lag can occur between capital output and capital stock (Ayres and Warr, 2005, p. 184).

Further they introduce the measure of useful work actually performed as a third factor of production. The choice of considering this last step in the exergy flow is due to the fact that previous steps taken for comparisons are still not reliable for comparisons because of the change of efficiencies during time due to change of technologies or other factors (e. g. ambient temperatures). The major part of final exergy is unproductive as it is converted into heat losses. Thus, the conversion efficiency is introduced as a variable in economic modelling which is further specified as the measure of exergy efficiency (Ayres and Warr, 2009, p. xxi).

An effort is taken to understand the long-run relationship between energy consumption and economic growth. The relative importance of energy conversion has changed over time. In developed countries the economy shifted away from energy intensive industries towards less energy intensive service activities (Warr and Ayres, 2010, p. 1688).

When testing related hypothesis for the US economy, Ayres and Warr (2005) find that exergy converted to useful (physical) work along with capital and labour explain output and drives long-term economic growth. The goal is to endogenize the technological progress as far as possible into the economic growth model.
In their analysis, they reject the use of exergy or energy as a third variable in the production function, because for the case of the US, GDP grows also faster than capital, labour and energy or final exergy. The term used in this context for the thermodynamic efficiency is not related to the term of economic efficiency (Ayres and Warr, 2005, p. 183).

Other variables can be considered to examine economic growth, i. e. energy prices, consumer price index, money supply and government spending (Warr and Ayres, 2010, p. 1689). That provides a structure of the energy service demand like heat, light and mechanical drive.

In Ayres et al. (2003) the economic growth mechanism is described as a feedback process. That means, that the output of an economy is the driver for the economy at the same time.

Another reason for economic growth is the rebound effect, which means that the cut of costs due to efficiency improvements and savings due to increased efficiency the remaining money can be used for further investment (Ayres et al., 2003, p. 251).

Ayres and Warr (2005) assume that electrification might have been the single most important source of useful work for production of goods and services, and the most important single driver of economic growth during the 20th century.
The authors propose that the simple assumption of the Cobb-Douglas function as economic growth function is not sufficient, because the growth process is a positive feedback cycle. That means that resource flows, i. e. exergy flows are both a cause and consequence of growth.
The assumed link between factor payments and factor productivities gives the national accounts a direct and fundamental role in production theory. However, the link might be spurious, because the economy does not produce final products neither directly from raw materials, nor from capital and labour.

Warr and Ayres (2010) examine the causality between the quantity and quality of energy consumption and economic growth. The correlation is observed for the US economy whereas a causality is not found.
In the next step it needs to be determined if there is any correlation or even causality between useful work and economic growth. The authors examine how economic growth can be stimulated. They examine the increase of exergy content of energy, the energy efficiency and the adaption of the pattern of energy service demand. Those factors are identified rather than just the increase of total energy and exergy consumption (Warr and Ayres, 2010).

Warr and Ayres (2006b) create scenarios for the US economy for 2000 to 2050. They argue that the neoclassical theory fails to describe the role of materials and energy consumption in the economy (Warr and Ayres, 2006b, p. 330).
Energy consumption is considered only as a consequence of growth, and not a driver of growth (Warr and Ayres, 2006b, p. 331). That is in contradiction to the observation that energy scarcity, that is caused by energy price increase does affect the economy (Raeth, 2009).
Instead of the exogenous driver of technological progress two learning processes are included into the model (Warr and Ayres, 2006b). Exergy service or useful work describe the productive inputs derived from materials and energy into the economy.

The technological progress is defined as a measure for the aggregate efficiency of conversion of energy into useful form.

The long term relationship between energy consumption and economic growth has been analysed (Warr and Ayres, 2010). The relative importance of energy in economies has changed over time, due to the shift of economy away from energy intensive industries towards less energy intensive service activities. Production is shifted to other countries which means that the energy consumption is not reduced but shifted by the same amount to a different country - or even with higher energy consumption because of less developed technology and experience in other countries. Warr and Ayres (2010) conclude, that evaluation methods are needed to make a statement about the evaluation of measures for efficiency improvement. That means, that producing companies can invest in increasing exergy efficiency in order to benefit from the increased supply of useful work while having the same amount of exergy consumed (Warr and Ayres, 2010, p. 1693).

Having the abstract exogenous technical progress in the economic growth function provides the disadvantages that future economic growth is assumed to continue at historical rates and secondly alternative sustainable scenarios cannot be explored, because the relation between economic growth, technology and natural resources are ignored.

Warr et al. (2008) find, that the improvements of efficiency with which fuel exergy is converted into useful work is a significant driver of growth.

Currently it seems, that the economic system depends on the high input of fossil fuels, rather than on considerable efficiency gains. The authors do not deliver an explanation whether a reduced reliance on fossil fuels and a reduction in carbon emissions might be achieved without considerable reductions in GDP.

The measure of energy intensity of a country provides the relation between the use of energy and the economic output represented by the GDP. The elasticity of energy has been increasing during the last decades from 0.7 in the 1970s to 0.4 in the 1990s until 2002.

The energy elasticity of and economy describes the increase of energy demand per unit of increase in GDP.

Further it is pointed out, that historically the improvement of exergy conversion-to-work efficiency contributed to technical progress. More specific, that means a reduction of cost and price through the whole downstream value added chain.

For more recent years, after 1975, it is suggested, that either energy conversion and system optimisation triggered by the energy price spike or the additional value creation of information and communication technology (ICT).

They conclude with the statement, that if economic growth is to continue without proportional increases in fossil fuel consumption, it is vitally important to exploit new ways of generating value added without doing more work. Developing ways of reducing fossil fuels exergy inputs per unit of physical work output is going to be essential. Exergy conversion efficiency is probably the main key to long term environmental sustainability.

Lindenberger (2003) examines the German service industry using the Cobb-Douglas production function. The energy demand is included into the model besides the factors of production capital and labour to enable the model to analyse the technological progress. The application of the model for Germany shows that the output elasticity of energy does not match with its cost share as it is assumed for capital and labour.

A project named MEET2030 was carried out in Portugal, with the goal of developing scenarios for 2030 for Portugal taking into account energy efficiency, the 4th industrial revolution and the need for a low carbon economy (Alvarenga et al., 2017). Macroeconomic and energy data was analysed to examine historical data of useful work consumption in Portugal and identifying a link between the final to useful aggregate exergy efficiency of Portugal and its economic growth. Following a participatory approach, the project provides scenarios which were developed with experts from science and industry to obtain robust results. The output were two contrasting scenarios for Portugal for 2030. The first includes more optimistic assumptions, the second represents a business as usual scenario. The scenarios point out some of the crucial parameters to focus on for a low carbon economy. The methodology of this thesis is based on the one used in the MEET2030 project. It examines if the findings from the historical data for Portugal also apply to Germany. In contrast to the project carried out in Portugal, this work is based on existing forecasts and scenarios for the future development rather than a participatory scenario building process.

Chapter 3

Method

In this chapter, the methods for data analysis and for scenario development are described. First, data for Germany is collected and the data analysis is conducted considering macroeconomic and energy data. Second, the economic model is set up and a statistical analysis is executed to examine the link between the total factor productivity as a macroeconomic measure and the aggregate efficiency as a thermodynamic measure. Third, the results are used to develop and examine scenarios up to 2030. The macroeconomic parameters capital and labour as well as the energy parameters useful work and aggregate efficiency are considered.

Based on the work of Ayres and Warr (2009) and Serrenho et al. (2014) the economic model is considered to analyse the economic growth within the past years taking the exergy consumption into account. Due to the availability of data, the time period between 1970 and 2014 is considered to examine Germany's historical data.

3.1 Data Collection and Analysis for Germany

3.1.1 Estimating the Contribution of Production Factors to the Gross Domestic Product

The aspects of economic growth according to the neoclassical model of SOLOW are analysed. These aspects are based on the assumption that the production factors capital and labour together with the total factor productivity contribute to the economic output. In the first place, macroeconomic data for capital, labour and GDP is used to apply the economic growth model for Germany. As described by the Cobb-Douglas function in section 2.1 the contribution of capital and labour is weighted according to the labour share and the capital share (Solow, 1956, 1957). The macroeconomic data of Germany is provided by the Penn World Table 9.0 (PWT 9.0) database which contains national-account data from 1950 to 2014 (Feenstra et al., 2015). The case of Germany shows difficulties in the analysis of long time series.

In PWT 9.0 the data for the gross domestic product is determined for the time before the reunification of Germany, by using common methodology. Based on the growth rates of West Germany, the data for unified Germany is approximated (Feenstra et al., 2015). Even though this way of calculation is the common practice to determine the GDP of Germany, it is based on the assumption that economic growth occurred equally in both parts of Germany and leads to inaccuracy.

For the historical observation, three different definitions for Germany have been used. The AMECO database provides data for Germany before the Second World War, West Germany after the Second

World War and unified Germany after 1990 (European Commission, 2018b). Labour shares are presented for the period from 1925 until 2010 excluding the time period of the Second World War and five years of post war time (Schneider, 2011).

In the economic model it is assumed that around one third of the generated income of an economy (measured through GDP) is spent on capital, whereas around two third are spent on labour.
According to the data in the PWT 9.0 the approximation is reasonable for Germany. The values for labour fluctuate around the two-third value. The data up to 1990 is assumed as constant. More precise data of the labour share only exist for West Germany until 1990. Due to the lack of reliable data for unified Germany the assumption from PWT 9.0 is used for the calculation.
Thus, it is further assumed that both capital and labour contribute to GDP with the constant share.

The following examination is based on the economic growth model described by SOLOW were the economic output depends on the two production factors capital and labour (Solow, 1956).
Due to the fact, that the data is not consistent during this time period, the averaged value given by PWT 9.0 is taken for the following calculation as described in section 3.1. Using the data for capital, labour and gross domestic product from PWT 9.0, the macroeconomic data is analysed for Germany in section 4.1.

Specifically, the time trend of GDP is compared to the trend of capital and labour as relative values to the value of a base year to visualise the growth during the observed time period. Including the total factor productivity, the economic output is presented as the production function in Cobb-Douglas form. The Cobb-Douglas function is given with Equation 2.3 in chapter 2.

In this thesis, the measure of GDP is considered as reasonable for the purpose to analyse the economy in regard to exergy consumption. Since this thesis is rather targeting the pure economic point of view, than the question of sustainability in regards to natural resources, the measure of GDP is sufficient for the following analysis. However, it is considered as a reasonable measure for the purpose of the thesis.

Using the provided data, the TFP is determined. Labour is corrected by including the education level to the absolute values of hours worked by considering the human capital index.

In the first step, the Cobb-Douglas function is applied for Germany. Therefore, data for the two production factors is considered as well as the factor shares and the economic output. The economic output Q is measured in monetary values by the gross domestic product (GDP). The absolute value of GDP can be compared to the absolute value of the first year of the time series 1950. It is thus expressed as an index value. The absolute value of the economic output in year 1950 is considered as Q_{1950}, whereas the relative value of the output is defined as $q_t = Q_t/Q_{1950}$. Correspondingly $k_t = K_t/K_{1950}$ and $l_t = L_t/L_{1950}$ are defined. So that $q_{1950} = k_{1950} = l_{1950} = 1$.

It is assumed, that the returns to capital can be equated to payments to capital. The same is assumed respectively for labour. The labour share, also called the wage share, gives how much of the national income is distributed to labour and how much to capital (Schneider, 2011).
In this model of two factors of production, the shares are approximated with $\alpha = \frac{1}{3}$ and $\beta = \frac{2}{3}$. Thus, a constant return to scale is implied so that the shares add up to one ($\alpha + \beta = 1$).

The amount of labour as a factor of production is determined by using the number of people engaged and multiplying the annual hours worked per capita. The total annual hours worked are corrected with the human capital index (HCI) in order to include the education level into the measurement of working hours. The HCI allows it to compare the productivity of hours worked between different education levels and over time (Schwab, 2017)

The Cobb-Douglas function described in Equation 2.3 is used with the constant shares of $\alpha = \frac{1}{3}$ and $\beta = \frac{2}{3}$. It includes the multiplier $A(t)$ as a time dependent value. The multiplier represents the total factor productivity (TFP). The TFP increases over time, so it reaches roughly four times higher value than the one of the base year. That means, technology quadrupled the productivity of the economy over these years.

Assuming that the growth rate of GDP relates to the growth rate of capital and labour weighted according to their contribution to GDP leads to Equation 3.1.

$$(kl)_t = \frac{K_t^\alpha L_t^\beta}{K_{1970}^\alpha L_{1970}^\beta} \tag{3.1}$$

On basis of the process of the methodology of the MEET2030 project, the macroeconomic and energy data is connected so that the analysis according to the exergy economic approach can be executed (Alvarenga et al., 2017). The model is verified for the case of Germany.

3.1.2 Estimating Useful Work

The energy data is taken from the World Energy Statistics from the International Energy Agency (IEA), which provides energy balances for OECD countries between 1960 and 2014. The IEA provides data about the supply, demand, export, imports and storage of both primary and secondary energy carriers. The data is presented for all economic sectors of industry, transport, energy industry own use and others, broken down by energy carriers. Before 1970 only West Germany is considered, whereas from 1970 onwards the new federal states are included into the data. The structural break causes an inconsistency in the graphs for this year.

Each energy carrier in the economic sector is assigned to an end use. Thus, the second law efficiency for each technology used in the economic sector is determined. The calculation provides the total useful work consumption of each economic sector and for the entire economy. Based on that, the data is analysed more detailed. Final exergy and useful work data is presented for the economic sectors, as well as the second law efficiencies for the economic sectors.

Primary energy carriers provide the energy directly from natural resources. The energy is embodied in the natural resource, while it can be extracted by using a transformation process. Primary energy carriers are e. g. oil, coal, water, solar, wind, gas and wood which is not further processed.

The total primary energy supply gives the energy content of all primary energy carriers that are used inside the country. It is calculated by summing up the energy production of primary energy carriers within the country, their imports and exports and changes in storage. Exports are accounted as negative values.

As described in chapter 2, the final energy is the energy delivered to the end user. The final energy consumption is given in the data sheet, which is shown in Figure A.6. The final energy consumption is the sum of consumption in the end-use sectors, which are industry, transport, energy industry own use and others. The data of the IEA database presents values for every energy carrier (i) for the use in economic sector (j) and year (t).

Based on the mapping of useful work end use categories each energy carrier is assigned to an end use within the economic sector it is used (Serrenho et al., 2014).

The exergy is calculated according to the type of energy carrier (i) by using the exergy factor (ϕ).

From the data for the final energy demand (E_F) the final exergy consumption (B) is calculated. Therefore, each energy value is multiplied by the referring exergy factor:

$$B_{t,i} = E_{F,t,i}\phi_i \tag{3.2}$$

where ϕ_i is the exergy factor of each energy carrier. The exergy factors are taken from the table in Serrenho et al. (2014) which are presented in Table 3.1.

Table 3.1: Exergy Factors According to Serrenho et al. (2014)

Energy carrier i	Exergy factor ϕ
Coal products	1.06
Oil products	1.06
Coke	1.05
Natural gas	1.04
Combustible renewables	1.11
Electricity	1.00
CHP and geothermal heat	0.40
Solar thermal heat	0.25
Other	1.00

To determine the next stage in the exergy flow the useful work is calculated. The useful work consumption (U) is calculated by using Equation 3.3.

$$U_{t,ijm} = E_{F,t,ijm}\phi_i\varepsilon_{t,m} \tag{3.3}$$

To calculate the useful work the value of final exergy for every year and type of energy carrier in each sector is multiplied with the second law efficiency that is depending on the end use category and year $\varepsilon_{t,m}$. Where m is the exergy end use category.

With the values for the final exergy and useful work consumption, the aggregate efficiency is calculated. That means, on an macroeconomic level, that the whole exergy consumption of one year, considering each type of end use, is used to calculate the aggregate efficiency. The disaggregated end-uses are summed up. The useful work of the whole economy is considered as one aggregated value. The ratio is determined according to the following equation:

$$S_t = \frac{B_t}{U_t} \tag{3.4}$$

where S_t is the aggregate efficiency value for one year.

In order to apply the economic growth model for the case of Germany, both the macroeconomic data and the energy data is analysed in chapter 4.

3.2 The Exergy Economy Model

To connect the findings from the macroeconomic analysis and the findings from the energy data, the first step was to determine the exergy intensity of the economy.
In the second step the aggregate efficiency is considered as a potential explanation for the total factor productivity. In the third step both variables are examined for a statistical relation.

3.2.1 The Energy and Exergy Intensities

The intensities are determined in four steps. The primary energy intensity is defined with Equation 3.5. The ratio describes the amount of primary energy that is required to obtain a unit of economic output. The ratio is calculated for final energy, final exergy and useful work. The ratios are given in Equation 3.6, Equation 3.7 and Equation 3.8.

In order to make a statement about the connection between exergy consumption and the economic output of a country, Serrenho et al. (2014) examined the final exergy and useful work intensity of several countries of the European Union. However, Serrenho et al. (2014) only presents the final exergy and useful work intensities in his work as a measure to evaluate an economy.

In this thesis, the approach is followed and extended by looking more detailed into the sectors and the conversion efficiencies.

The primary energy demand and the final energy demand is considered.
Considered is the time period of one year.

$$\text{(Primary Energy Intensity)}_\text{t} = \frac{\text{(Primary Energy Consumption)}_\text{t}}{\text{(GDP)}_\text{t}} \tag{3.5}$$

$$\text{(Final Energy Intensity)}_\text{t} = \frac{\text{(Final Energy Consumption)}_\text{t}}{\text{(GDP)}_\text{t}} \tag{3.6}$$

Analogue to that, the final exergy intensity and the useful work is determined in Equation 3.7 and Equation 3.8.

$$\text{(Final Exergy Intensity)}_\text{t} = \frac{\text{(Final Exergy Consumption)}_\text{t}}{\text{(GDP)}_\text{t}} \tag{3.7}$$

$$\text{(Useful Work Intensity)}_\text{t} = \frac{\text{(Useful Work Consumption)}_\text{t}}{\text{(GDP)}_\text{t}} \tag{3.8}$$

Annual values are considered for the analysis.

3.2.2 The Ratio of Total Factor Productivity and Aggregate Efficiency

In the next step, the ratio of the annual values of aggregate efficiency and total factor productivity is examined as a possibility to provide an explanation for the total factor productivity.

For Portugal it has been examined, if the total factor productivity (TFP) can be explained by the increase of aggregate efficiency (Alvarenga et al., 2017).
Therefore, both variables are expressed as an index value which is the relative value to the base year ($a_t = A_t/A_{1970}$ and $s_t = S_t/S_{1970}$).
For Portugal it turns out, that the ratio of the logarithmic values is roughly in the range of 1.3 and 2.3 with and average value of 1.87 for the considered time period from 1960 to 2014. It is examined, if the finding for Portugal, that the trend of TFP is connected to the trend of aggregate efficiency, also applies for Germany. The ratio is a suitable way to graphically compare the the evolving trend of both time series.

3.2.3 The Statistical Analysis

Further, it is examined if the trend of total factor productivity can be statistically connected with the trend of aggregate efficiency. Therefore, a suited statistical analysis is executed in order to find a correlation between both time series. A statistical analysis is executed in order to examine if the visually assumed

connection between total factor productivity and aggregate efficiency can be proved.
Based on the work of Ayres (2006) it is examined if the total factor productivity can be endogenized (Ayres, 2006, p. 182). An increase in thermodynamic efficiency of the economy is related to the measure of total factor productivity (Warr and Ayres, 2006a, p. 4). The finding that has been made in that work is examined for Germany.

3.3 Future Scenarios

Based on the analysis of aggregate efficiency and total factor productivity four future scenarios are developed to model possible trends for the coming years. Two different trends in the development of the transportation sector and two trends in the electricity production sector are modelled.

Therefore, parameters are defined that are considered for the scenarios. For the development of the future trends existing future pathways provided by official projections about population and developments in the transportation sector are taken into consideration as well as parameter trends that are determined by the past data.

Trends of the useful work data are extrapolated. The transport sector is considered in more detail. Projections for the use of electric vehicles, that implies a technological change and a change in exergy efficiency are used to develop scenarios. The transport sector is target for political discussions, decisions and for the environmental goals. Therefore it is considered in more detail.

The other sectors like industry, energy industry own use and others are assumed to continue the trend that they show within the recent past. Based on the development of useful work and the trend of second law efficiency the final energy is determined.

The scenarios are based on the analysis of section 3.2 and on published future pathways of industry sectors and the government. The parameters considered for the future scenarios are described in more detail.

Official forecasts of population development in Germany are used. The Federal Statistical Office provides projections for Germany's population until 2060 (Pötzsch and Rößger, 2015). The following calculation is based on these projection. These are based on developments considering life expectancy, fertility rate, number of births, migration and number of deaths.
The projections provide eight scenarios in total, of which two basic scenarios for the population development are chosen. One is based on an assumed lower immigration and the other one on an assumed higher immigration.

The development of the capital stock is considered in two development paths. The capital stock is calculated by using the capital stock of the previous year and add the investment based on the penultimate year's economic output and subtract the depreciated capital. The capital stock for each year is calculated with:

$$K_t = K_{t-1} + r_{t-1} GDP_{t-2} - \delta_{t-1} K_{t-1} \tag{3.9}$$

where the r describes the investment capacity (in % of GDP) and δ is the depreciation rate that quantifies the depreciation of capital stock over time. The numbers per GDP are taken from The World Bank (2018) database.
For the first scenario, a constant investment capacity is assumed, for the second scenario an annual increase of the investment capacity of 2 % is assumed.
The Penn World Table 9.0 provides data for the average depreciation rate of capital. The numbers are extrapolated to the next years. For both scenarios, constant depreciation is assumed.

Labour is calculated from the forecast for population. The forecast gives numbers of the population with an age between 20 and 65 years. Based on those numbers, which is the range of age of interest, the labour force participation rate (TP) is taken into consideration to determine the maximum of people that can be employed. The number of unemployed people is subtracted from this number. It is calculated by the unemployment rate (td). The number of employed people is multiplied by the average hours worked per person.

$$L_t = h_t(1 - td_t)N_{p(20-65),t}TP_t \tag{3.10}$$

N_p is the population size of Germany. annual hours worked per person (h) gives the annual hours worked per employed person. The population in working age, which is from 20 to 65 years old, will drop from today's 49 million to around 43 to 44 million in 2030.
Assumptions are made for the average hours worked as well as for the numbers of people with a part time job. The number of average annual hours worked is assumed to be constant until 2030. The HCI is assumed to be constant until 2030, which represents a constant education level of the labour force.

Scenarios are developed for the useful work consumption in each economic sector based on the historical development. The useful work consumption is used to determine the final exergy by using the second law efficiencies of the technologies that are applied in the sectors. With these scenarios the aggregate efficiency of the economy is determined which is linked to the total factor productivity.

Since political decisions target both the transportation sector and the electricity production sector the two sectors are considered in detail in the scenarios. The transportation sector is considered in detail, whereas the sectors industry, energy industry own use and others are considered on the aggregated level.

Three scenarios for the development of the transportation sector are given in literature for the amount of electric vehicles in Germany for 2030 (Rippel et al., 2018).

The first scenario (EV S1) assumes that one third of the car stock in 2030 will consist of electric vehicles. The second scenario (EV S2) that is provided by the Federal Network Agency assumes a number of 6 million electric vehicles for Germany in 2030 (Rippel et al., 2018).

The development of numbers of the car stock according to the technology in use does not provide a statement about the development of the useful work consumed by each technology. In tendency, the diesel and gasoline engines will further be used for long distance travels, whereas the electric cars are well suited for transportation within cities, that is rather for short distances. However, it is assumed, that the change in stock share goes along with the same change in useful work share.

Considering the two scenarios for shares of electric vehicles of the total stock of cars in Germany, one scenario with a high increase of electric vehicles is modelled and another one with a moderate increase.

An increasing of the total number of vehicles is assumed. Following the trend from the past years, the number of vehicle increases to 51 million in 2030 which goes along with the estimation of Shell in a study (Shell Deutschland Oil GmbH, 2009).
The numbers of cars in Germany are shown in Table 3.2 and visualised in Figure A.22.

The two scenarios are assumed with a constant amount of useful work needed. The assumption is made due to the fact, that the exergy service of transportation on roads is so far exploited and is not probable to change. Useful work consumption in the transportation sector is assumed as constant over time, because population is roughly stable, and the distances travelled per person are stable. That is

Table 3.2: Scenarios for the Development of Passenger Cars in Germany

		EV S1	EV S2
Number of vehicles x10^3	2014	2030	2030
Diesel vehicles	13,215	7,246	13,495
Gasoline vehicles	29,956	26,991	30,451
Electric vehicles	12	15,890	6,181
Other vehicles	752	1,010	1,010
Total	43,851	51,137	51,137

also assumed by Shell (Shell Deutschland Oil GmbH, 2009).

In the scenarios the development of electricity consumption and the generation of electricity is based on the national targets and national forecasts. Thus it is assumed, the goals for the share of electricity generated by renewable energies is as well considered as scenarios about the amount of electricity consumed.

The scenario calculation is done with the optimistic development, that the targets set are reached. A pessimistic scenario is developed, where the goals are not reached.

Two different scenarios for the electricity production are used to show the difference between the scenario when reaching the political targets and not reaching them. The first scenario (EL S1) is based on the assumption that the goals for the electricity production are reached so that the share of renewable energies reaches 50 % of the electricity supply. The second scenario (EL S2) is considering the case that the share of electricity supply by renewable energy sources remains constant and the political targets are not reached. Table 3.3 presents the shares of energy carriers used in electricity production in the development over time.

Table 3.3: Technology Shares in Electricity Generation

		EL S1	EL S2
	2014	2030	2030
Coal	43.7 %	35 %	43 %
Gas	11.74 %	14 %	26 %
Oil	0.75 %	0.5 %	0.5 %
Combustible renewables	9.06 %	10 %	10 %
Non-combustible renewables	18.95 %	40 %	20 %
Others	0.32 %	0.5 %	0.5 %
Nuclear	15.23 %	0 %	0 %

Based on the two scenarios for the development in the electricity generation sector the impact of the electricity generation is calculated for both electric vehicle scenarios.

In political discussions, several scenarios are discussed in order to reach both, the international and the national climate goals. On the international level, the Paris agreement is the recent guideline that describes the pathway to follow for the coming years.

The government coalition in Germany since this year, agreed on the following steps to take in order to reach the goals set.

However, according to the Federal Office of Environment the measures taken by the government are not sufficient to achieve the target state (Pfeiffer et al., 2017).

Until 2030 the GHG emissions have to be reduced by 55 % compared to 1990. The share of electricity generated with renewable energies should reach 55 to 60 % in 2035, That would imply a share of around 50 % in 2030. The gross primary energy demand should be reduced by 20 % in 2020 compared to 2008. The goal for 2050 is a reduction by 50 %. Assuming a linear reduction, that would mean a reduction of 30 % by 2030 (Rippel et al., 2018).

3.4 Primary Energy Equivalents

Since political decisions usually target the primary energy step, the final energy is converted to primary energy equivalent.

The primary energy equivalent for renewable energy carriers can be determined in different ways. The four main methods are:

1. Zero equivalent method
2. Direct equivalent method
3. Physical energy content method
4. Substitution method

Those different methods account the amount of primary energy that is contained in renewable energies in different ways. It is distinguished between combustible and non-combustible energies.

The most commonly used and here discussed methods are the physical energy content method and the substitution method.

For the physical energy content method, starting from the renewable energy source, always the first usable form of energy is accounted as the primary energy. That means for renewable energy forms that directly produce electricity such as solar, wind, hydro, etc. the electricity is accounted as 100 % of primary energy (i. e. $1\,\mathrm{MW}_{\mathrm{el}} = 1\,\mathrm{MW}_{\mathrm{primary}}$).
For nuclear energy a value of one third is used to account the used nuclear energy carrier as a primary energy value.
The physical content method is used by statistics from IEA and Eurostat.

The substitution method assumes the amount of the first energy form involved as the primary energy. That is for example the kinetic energy of wind for wind turbines. In praxis, to avoid the calculation for each technology itself, the efficiencies of the fossil fuel power plants are taken, that are replaced by the renewable energy source or the amount needed to be replaced.

Since the physical energy content method is used by the IEA, it will also by applied here. However, considering the way of accounting the primary energy from renewable energy carriers, changes a lot the development of total primary energy used within the country. That affects as well the targets of the climate goals.

Since those named methods to not capture other benefits of using renewable energies, the FRAUNHOFER INSTITUTE suggests using primary energy factors smaller one. The difference between conventional and renewable energy carriers is small using the physical content method Esser and Sensfuss (2016). Data for the efficiencies of power plants to generate electricity is taken from the data of Taylor (2008)

Chapter 4

The Link Between Exergy and Economic Growth in Germany

This chapter presents the results from the methods described in section 3.1 and section 3.2. Further, conclusions are drawn about the historical development and the findings are analysed. These results are used for developing scenarios in chapter 5.

4.1 Economic Growth in Germany

In order to visualise the growth of the economic output the index values are presented in Figure 4.1. The index values show the annual values as a relative value to the base year 1950. To visualise the contribution of the two production factors capital and labour to the gross domestic product, their index values determined by Equation 3.1 are presented in Figure 4.1. As described in section 3.1 the production factors are weighted according to their monetary shares. Detailed historical data of gross domestic product, capital and labour is shown in Figure A.1, Figure A.2 and Figure A.3.
In the first step labour is considered as total annual hours worked. Comparing the result of Equation 3.1 to the real development of GDP a gap between the two curves is observed. That means the assumption of considering only the two production factors to determine economic output is not sufficient to explain economic growth in Germany.
In the second step labour is corrected by including the correction factor for education HCI. The gap between the economic output and the contribution of the production factors decreases. However, including the schooling correction is still not sufficient to explain the economic output. Both labour measured in total hours worked and labour measured in schooling corrected total hours worked is presented in Figure 4.1.

The economic output increased by eight times from 1950 until today. However, the growth of capital and labour according to their share increased by only 1.9 times. To take the change of education for labour into consideration, the measure of the human capital index is included to the calculation. The multiplier represents the fact, that the education level of workers increased over time so that the hours worked became more productive.
Considering the education level with the human capital index (HCI), it increased by 2.5 times.

According to the neoclassical economic growth model, the gap between the contribution of the two production factors and the economic output is described by a time dependent multiplier that represents the total factor productivity.

Equation 2.3 provides the multiplier that represents the total factor productivity. It is calculated in

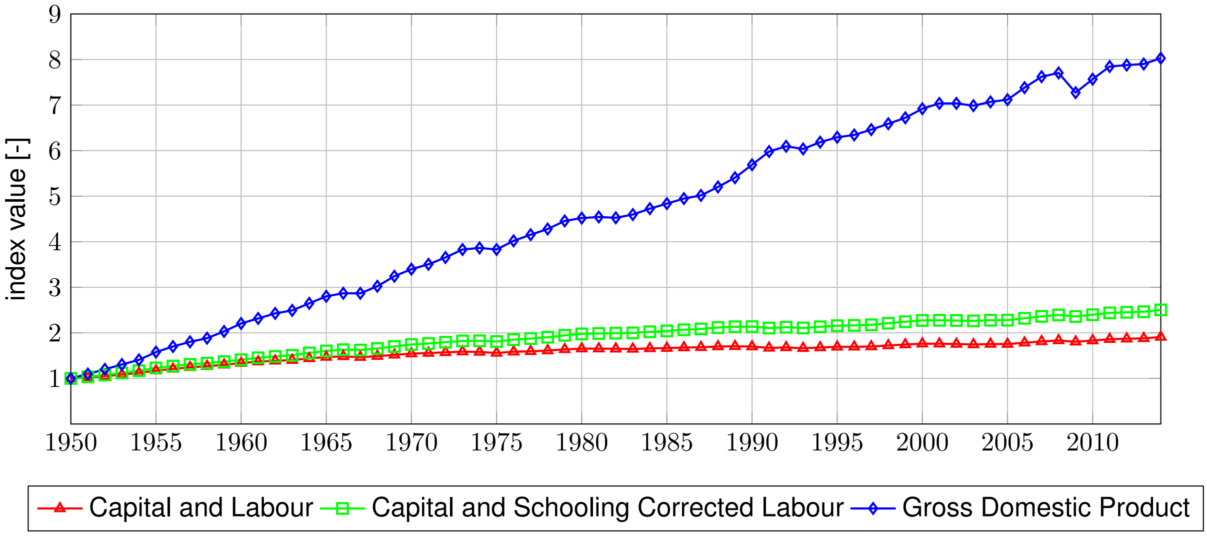

Figure 4.1: Contribution of Capital and Labour to Gross Domestic Product

two ways. First, considering the total annual hours worked. The factor evolves from 1.8 to 8 over time. Second, the schooling corrected total annual hours worked are used for the calculation. In this case the factor evolves from 1 to 3.3. Both time series are presented in Figure A.4.

For the following calculation the schooling corrected labour is considered as the factor of production. Correcting labour by the education level is the first step to give an explanation for the increase in productivity over time. However, the explanation is not sufficient. It is further examined, how the increase in productivity can be explained.

Looking at the historical development of Germany's economy the presumption is obvious that there is a link between the energy supply and the economic output in Germany. Several recessions occurred in the history of Germany after the Second World War that can be seen by negative growth rates of the gross domestic product. The time period shown starts after the Second World War. After Germany has been destroyed by the end of the Second World War the reconstruction took place. A lack of food supply occurred in Germany in 1946/47. At the same time Germany was lacking coal supply. Coal was the most important energy carrier after the Second World War. It was an essential energy source for private households, transportation and industry. The coal mining was highly regulated by the Allies and it was sold below prices of the world market. Coal mining was inefficient due to old machines, lack of labour force qualification, the age structure and the lack of proper distribution networks within Germany.

The British and the American governments were interested from the beginning on, that Germany is brought to a state in which Germany was independent from other countries.
The American president considered it as inevitable to bring Germany's economy to a strong level in order restore the productivity of Europe's whole economy.
The currency reform took place in 1948 already in order to get rid of the barter trade.

In 1949 the Federal Republic of Germany (FRG) was founded in West Germany. In the same year, the German Democratic Republic (GDR) was founded in East Germany.
From that point onwards, the economy started growing in Germany. However, there have been six recessions in Germany after the end of the Second World War. The economy experienced a boom between 1950 and 1967 that let the economic output grow with and annual growth rate of up to 12 %.
The first recession happened in year 1967 in the end of the economic revival of Germany's economy, called the German "Wirtschaftswunder". From the following year on, the economy continued grow-

ing (Federal Agency for Political Education, 2005).

The economic growth continued until the oil price crisis. The two following recessions came along with the oil price shocks in 1973/74 and 1980. In 1973/74 the oil prices increased significantly. The measurable effect on GDP occurred delayed in 1975 with a negative growth rate for GDP. The second oil price crisis took place in 1979/80. The impact on the economic output of the economy was again delayed to 1982. Thus, negative growth rates of GDP can be observed in 1975 and 1982. Due to the Iranian Revolution, the oil production has been reduced which went along with an increase in oil prices. The development of the oil price shows significant peaks in those years (Macrotrends, 2018).

In the end of the 1980s Germany has been reunified. The economy in East Germany was poorly developed at that point in time. After the reunification, the German economy suffered, the unemployment rate increased and companies especially in the steel production (Thyssen AG), coal production (Ruhrkohle AG) and the automotive industry had to reduce the number of employees.

After the reunification of Germany, a boom happened, that delayed the next decrease of GDP to year 1993. The German economy continued to grow until the beginning of the 2000er.

In 2003 another recession happened after the terrorist attack of 11th September 2001 that caused an increase in oil prices in the following.
Also the financial crisis in 2008 preceded an increase in oil prices that had an impact on the whole price level of all energy carriers (Raeth, 2009).

The stock broking increased and a lot of companies launched at the stock market. In the period between 2000 and 2003 the German Stock Index (DAX), decreased continuously, while a slump in GDP occurred in Germany in 2003 (wallstreet:online AG, 2018). The terrorist attack in 2001 was also one of the reasons, why the world's trading system got influenced.
In 2007 the next financial crisis began. Stocks began to lose their value. The crisis arrives soon in Germany, so that the stock market began to break down and raw materials prices start to increase.
The European government decides to support banks financially. The crisis caused the most severe decrease in GDP after the Second World War (Siemens, 2009).
The historical view suggests a connection between economic growth and energy supply. Therefore, this connection is further examined using the exergy economy approach. AYRES and WARR identify exergy efficiency as a measure that can explain the total factor productivity.

In this analysis based on the SOLOW model (described in section 2.1) is shown that for the case of Germany, the assumption, that capital and labour are responsible for the economic output, is not sufficient. The endogenous variable TFP is still needed to obtain the measured output. Correcting the labour by a measure of education slightly reduces the residual.

Based on the work of AYRES and WARR, the next step examines the useful work consumption in Germany and the conversion efficiencies to analyse the findings for Germany.

4.2 Useful Work for Germany

Due to the conditions of the data described in chapter 3, the time period from 1970 to 2014 is considered for the analysis of the energy data. In the year 1970 a sudden increase in energy demand data is observed. This jump is due to the consideration of the new federal states of Germany from 1970 onwards in the statistics. Thus the development of the energy data is only reasonably considerable and comparable from 1970 onwards.

Based on the data of final energy demand, the final exergy and useful work consumption are determined. Both time series are presented in Figure 4.2. The total primary energy supply with its components and the final energy demand are shown in Figure A.5 and Figure A.6. To verify the calculation the results are compared with data for energy demand provided by national data bases.

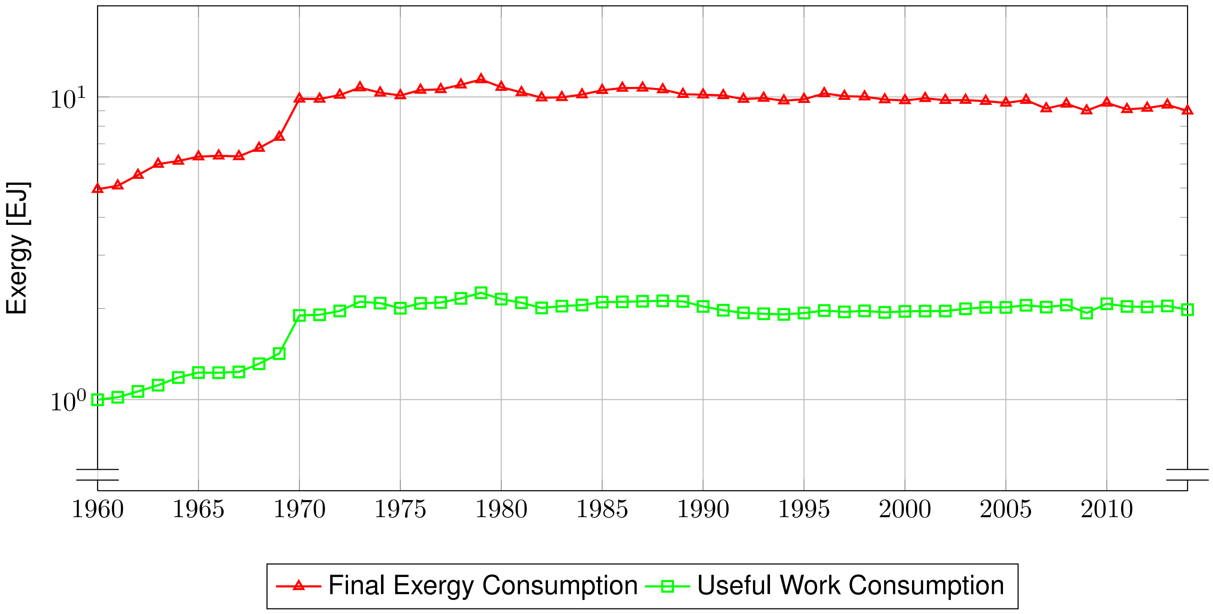

Figure 4.2: Final Exergy and Useful Work Consumption in Germany from 1960 to 2014

The exergy values are close to the energy ones. The slightly decreasing trend of the curve over time remains.

Serrenho et al. (2014) used the different end uses to convert first law energy efficiencies to second law efficiencies by using information about the surrounding temperature in which the technology is used. Low temperature heat is predominantly used for residential heating which is only used in winter. Therefore the average winter temperature is used to determine the second law efficiency.

For each sector the disaggregated end use is assigned to the energy carrier to determine the second law efficiency of each end use for every year. The end use categories are shown in Table A.1.

The second law efficiencies are taken from the calculation in Serrenho et al. (2014) where the time series until 2009 are examined. In order to obtain the values up to 2014, the efficiency is assumed as constant in these five years after 2009.

Muscle work of animals and humans is neglected at this point even though it is still included by Serrenho et al. (2014). However, it has a negligible share in Germany.

The useful work is constant from 1990 onwards. A clear drop is observed in 2009 due to the financial crisis.

It becomes visible that the values for useful work are stable over time and have not varied much during the past four decades.

The curve for final exergy is slightly decreasing. That means, that the gap between the two curves is getting smaller, which goes along with the increase aggregate efficiency to convert exergy from the final to the useful stage, that is shown in Figure A.7.

The trend of the aggregate efficiency over time is shown in Figure A.7. It is observed that the final to useful aggregate conversion efficiency is between 19 % and 22 % in the observed time period between 1970 and 2014.

The trend is a slight increase efficiency during the past two decades, whereas it was roughly stable in the time before 1995.

Looking at the relative development of exergy and useful work consumption gives the following graph Figure A.18. Year 1970 is set as a reference value to which the value for the following years is compared. From 1970 to the mid 1990s the development of final exergy and useful work is closely linked and the curves follow a similar path. The efficiencies used by Serrenho are based on assumptions and the trend is considered either as constantly increasing or being constant over time.
From 1998 onwards the two curves diverge whereas the useful work stays approximately on the same level and the final exergy has a decreasing tendency.

The share of final exergy consumption of each economic sector of the entire economy is presented in Figure A.8. The share of useful work consumption of the four main sectors of the total useful work is shown in Figure A.9.

In the industry sector requires the major share of useful work consumption. That is due to the energy intensive industry sectors that are operating in Germany. These sectors are chemical and petrochemical, iron and steel, non-metallic minerals, machinery, paper, pulp and print, food and tobacco and transport equipment.

However, the final exergy consumption covers only one fourth of the total final exergy consumption. In these industry sectors technologies with higher efficiencies than in other sectors are used. That is why the share of the industry doubles from the final to useful stage.

The final exergy consumption in the industry sector is shown in Figure A.10 and the useful work in Figure A.11. The chemical and petrochemical and the iron and steel industry have the highest useful work consumption. Also for the final exergy consumption they have the highest share. In these sectors technologies with high second law efficiencies are used.

The overall second law efficiency of the industry sector is nowadays around 41 to 42 % and therefore much higher than the aggregate efficiency of the economy.

The transport sector has a share of one fourth of the total final exergy consumption. Since transportation increased over the years, both the final exergy and the useful work in that sector increased.

The technology that is used in this sector has an efficiency below the aggregate efficiency. It is in the range of 10.5 to 13 %.

The transport sector contributes to one eighth to the overall useful work consumption in Germany. Within the transport sector the share of road and rail transportation are the major ones. Both contribute to more than 80 % of the useful work consumption. The contribution is shown in Figure A.14.

In passenger transport the exergy service of transportation was used to travel around 15,000 km per person in year 2010.
Three fourth of the transportation is done by individual traffic and around 15 % by train and local public transport with equal shares (Hütter, 2013). That points out, that in Germany the most important way for passenger transport is the car with the highest share of useful work consumption. Therefore it is evident, that national goals target the development of technology in that sector.

That goes along with the observation, that in Germany the individual transport is the major choice for transportation. The second law efficiency of diesel or gasoline vehicles is in the range of 10 to 12 % which is quite low in comparison to other technologies. That is why in this field, the second law efficiency has to be improved to decrease final exergy consumption. The way that is intended by the German government is the electrification of vehicles, which leads to a higher second law efficiency for the technology

in use and a reduction in primary energy demand due to the electricity generation through renewable energy carriers.
For transportation, the amount of useful work consumed has to be decreased by finding more efficient ways of transportation, i.e. incentives to increase the use of public transportation, the better capacity utilisation of cars, improving the ratio of mass transported and mass of vehicle.
However, for the scenarios created in chapter 5, it is assumed, that the useful work consumption remains constant over time, due to a constant distance travelled per person per year.

In the sector that is including residential energy demand is named as others. The share of residential heating contributes to more than half of the useful work consumption. In this sector, the useful work demanded can be decreased by reducing the losses in buildings. Thus the improvement of insulation and construction and architecture is necessary.

For the energy industry own use, the sectors oil refineries and own use in electricity, CHP and heat plants are the highest consumers of useful work.

4.3 The Link between Aggregate Efficiency and Total Factor Productivity

The first step to link the macroeconomic data with the useful work is the examination of the ratio between exergy consumption and economic output. The ratio is called the energy respectively exergy intensity of an economy. The useful work consumption is constant since the 1970s whereas the GDP is growing with a constant rate over time. Useful work consumption remains at a level of around 2000 PJ per year.

Since the useful work consumption in Germany is roughly constant over the observed time period and the GDP has an increasing trend, both the final exergy intensity and the useful work intensity are decreasing. The useful work intensity is decreasing over time until it reached 0.77 MJ/€ in 2014. The decreasing trend of the intensity is attributed to the increase in GDP.

The ratio of energy supply and economic output is calculated as well. The primary energy intensity, the final energy intensity, the final exergy intensity and the useful work intensity are shown in Figure A.17.

Since the useful work intensity is changing over time a conclusion about the trend that it is following in the next years cannot be drawn. The trend is decreasing, however, the useful work intensity will converge to a threshold value in the future. The value will represent the minimum amount of useful work that is needed to ensure a unit of economic output. Based on this analysis it is not possible to draw a conclusion about an absolute threshold value which the German economy is approaching.

In order to compare the exergy intensity with the useful work intensity, for both measures the index values are taken to compare both development. Compared to the base year 1970, the useful work intensity decreased to less than half of the initial value. The graphs are presented in Figure A.18. The primary energy intensity decreased by two third of the initial value.

A further conclusion about the useful work intensity and the economic growth is not possible. Therefore, the useful work is further analysed.

4.3.1 Aggregated End Uses

The useful work consumption is further analysed by their aggregated end use categories (shown in Table A.1) in order to examine trends that allow a conclusion in regard to its link to economic growth. The trend of the final exergy consumption of the aggregated end uses is shown in Figure A.19. To compare it with the useful work consumption Figure A.20 presents the aggregated end uses of useful work. Some tendencies are observed. The final exergy of mechanical drive is slightly decreasing between the end of the 1990s and 2014 whereas the useful work of mechanical drive is increasing during that period of time. That means an increase in efficiency for the final to useful stage.

To have a more disaggregated look on the useful work consumption it is presented according to the end uses and the sectors.

According to Figure A.21 examining the aggregated end use categories of useful work it turns out that nowadays the mechanical drive has the highest demand of useful work followed by high temperature heat. However, high temperature heat decreased after the reunification of Germany. Due to the close relation of high temperature heat and industry in Germany the effect of the financial crisis can be seen clearly in the high temperature heat consumption. The drop in high temperature heat shows the clear link of useful work consumption and useful work. However, it is not examined, if the decrease of useful work consumption is the direct result of the decrease of non-prospering economy.
Since the reunification, though, the high temperature heat has a slightly decreasing trend.
Whereas the mechanical drive is increasing with a constant trend.

Considering the development of useful work and useful work intensity, there cannot be a clear trend observed. From the graphs, it is not possible to draw a straight conclusion.

That is why the useful work is analysed with removing end uses in order to check if a trend can be discovered.

Apart from looking at the useful work considering the end uses, the data is checked for the sectors. The sectors industry, transport, others and energy industry own use is considered.

4.3.2 Useful Work Without Low Temperature Heat Uses

The major share of low temperature heat is used for residential heating. It is assumed that the residential heating does not provide economic value. That is why low temperature heat end use is removed from the calculation of the useful work intensity for testing reasons. Both the useful work intensity and the final exergy intensity are presented in Figure 4.3. Due to the low temperature gradient residential heating has a low second law efficiency. That is why the the aggregate efficiency increases when removing low temperature heat from the calculation.
However, the trend of both final exergy and useful work intensity remains similar to the consideration of the entire economy. Further conditions needs to be tested.

4.3.3 Useful Work Without High Temperature Heat Uses

High temperature heat is usually used in heavy industry, especially in steel and iron industry. Energy intensive industries produce building materials, chemistry, glass, non-iron metals, paper and steel (Verband Deutscher Papierfabriken e.V., 2018).

Removing high temperature heat considers the issue that some production processes are outsourced from Germany. Outsourcing production processes causes a shift abroad of useful work consumption. The useful work that is embodied in the materials is not considered in this approach so that the useful work consumption just disappears in case it it shifted abroad.

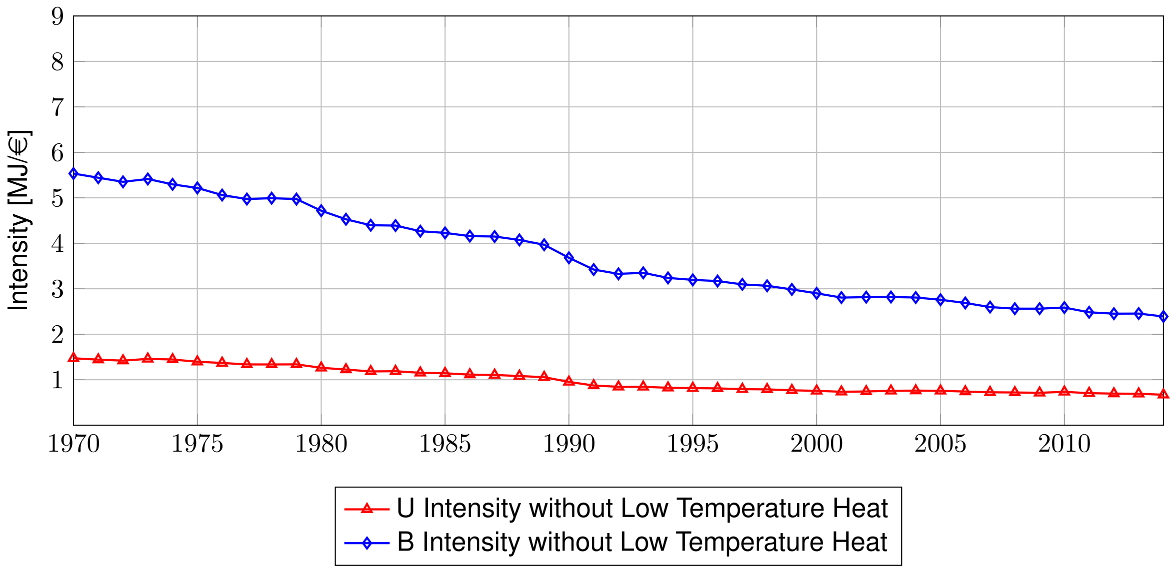

Figure 4.3: Useful Work and Final Exergy Intensity Without Low Temperature Heat Uses

Figure 4.4 shows that the trend of final exergy and useful work intensity remains in this case as well. Removing high temperature heat uses from the calculation does not reveal new insights on the useful work intensity.

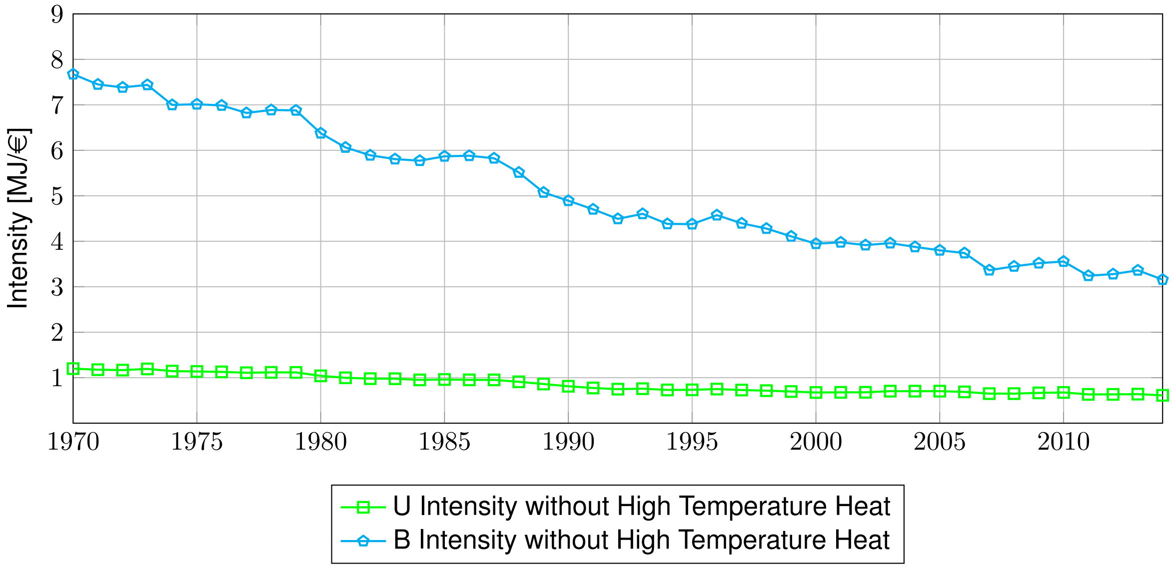

Figure 4.4: Useful Work and Final Exergy Intensity Without Low Temperature Heat Uses

4.3.4 Mechanical Drive

Since in Germany an increasing trend for useful work consumption in the end use mechanical drive is observed that trend is further examined. The increasing trend is presented in Figure A.20.

To examine if there is a contribution of mechanical drive to the total factor productivity, the mechanical drive is further split up into stationary and non-stationary mechanical drive.

The share of stationary mechanical drive is small in comparison to the one of non-stationary drive. That means, the increase of labour productivity cannot be explained by an increasing use of support by automation technology.

It is shown that mechanical drive can be used as stationary end use (industrial processes, etc.) or non-stationary end use (transportation). Splitting up the mechanical drive into the two categories stationary and non-stationary mechanical drive it turns out that between 60 and 80 % of mechanical drive are used as non stationary which is predominantly used in transportation, more specific in road and rail transport. The shares are shown in Figure A.16.
Around 80 % of the mechanical drive is used for diesel, gasoline and LPG vehicles consumed.

The non-stationary mechanical drive is almost entirely used for transportation on roads.
That means, that individual transport, public transport and transport of goods are responsible for the major share of mechanical drive consumption in Germany.

The disaggregated end uses are shown in Figure A.12. Therefore, the mechanical drive is further analysed.

Splitting up the mechanical drive according to their disaggregated end uses it turns out that non stationary used mechanical drive has the higher share of exergy consumed. Thus, transportation has the highest share of useful work.

Transportation does not contribute to GDP directly. Due to the fact, that Germany has a strong automotive industry that the use of mechanical drive for transportation is increasing, so that people buy more cars which is driving the economy.

The amount of useful work for diesel vehicles is increasing, whereas the amount of gasoline vehicle useful work consumption is decreasing. Summing up those two curves, the useful work stays constant since the 1990s. That means, the amount of travelled distance is constant.

In order to reduce the final exergy that delivers the useful work for the mechanical drive the conversion efficiency can be improved. Thus, it is inevitable to change from the low efficiency technology combustion engine to electric engines, which have conversion efficiencies up to almost 100 %.

The amount of cars existing in Germany has a slightly increasing trend.

In Germany the share of car brands from German car producer on the road is roughly two third over time (Zinke, 2018b). The trend of useful work for both diesel and gasoline vehicles shows that in past years, the transportation with diesel vehicles increased, whereas the transportation with gasoline vehicles decreased. That goes along with the statistics , that the number of diesel vehicles increased during the past ten years, whereas the number of gasoline vehicles remained constant (Zinke, 2018a).

The share of individual transport is around 75 % of the overall transport.

Numbers are provided by the Federal Statistical Office (Hütter, 2013).

4.3.5 The Ratio of Total Factor Productivity and Aggregate Efficiency

The approach considered in the MEET2030 project examines the trend in the logarithmic values of the two index values of total factor productivity and aggregate efficiency.

This method does not lead to reasonable results for Germany since the EFF index value remains close to one in several years which leads to high positive and negative peaks in the time trend of the logarithmic ratio.
Therefore, the ratio of the index value of the total factor productivity a and the index value of the aggregate efficiency s are taken to examine a first link between the two parameters. The ratio of the time series from 1970 to 2014 shows an increasing tendency between 1970 and 1989. In 1990 a clear structural break is observed which is considered in the following. From 1991 onwards, the increasing tendency

flattens out so that the ratio remains roughly constant over time at a value of 1.475.
The average ratio is shown in Figure 4.5 in the trend lines only for the time after the reunification of Germany. Both TFP and EFF are shown in Figure 4.5, including the ratio and the average value.

A statistical examination of the link between TFP and EFF is in section 4.4.

4.4 Statistical Relationship between Aggregate Efficiency and Total Factor Productivity

Due to the fact that Germany faced the reunification in 1990 a structural break occurs in the time series data. Therefore three ways of executing the analysis are described in the following. First, the structural break is not considered in the analysis. The second one includes the structural break by using the method suggested by PERRON and VOGELSANG (Perron, 1989; Perron and Vogelsang, 1993). The way of calculation and the results are shown below. Third, only the time series after the reunification of Germany is considered to execute the analysis for the short time series.

4.4.1 Germany from 1970 to 2014 without a Structural Break

The considered time series from 1970 to 2014 are presented in Figure 4.5. The application of the Augmented Dickey-Fuller Test (ADF) tests both time series total factor productivity and aggregate efficiency for unit roots and shows that both time series are non-stationary.

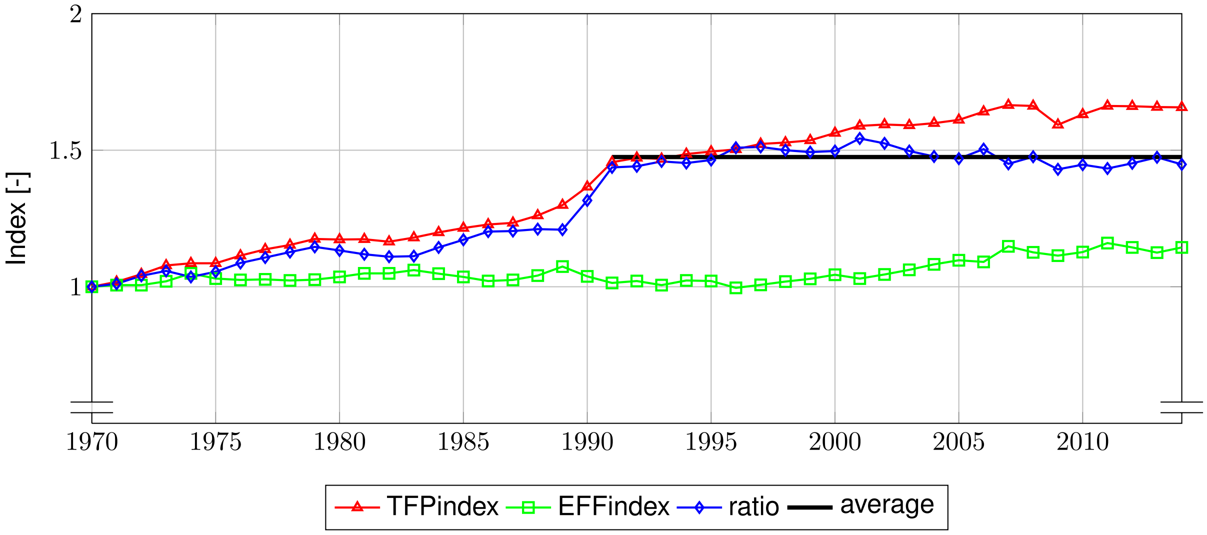

Figure 4.5: The Ratio of Total Factor Productivity Index and Aggregate Efficiency Index

The results of the shows, that the null hypothesis is accepted for both time series with sufficient significance. That means that there is a unit root existing in these time series.

The first difference of the time series is examined for unit roots. The Augmented Dickey-Fuller Test (ADF) test shows that for both time series the first difference, the null hypothesis is rejected. This means, with a sufficient significance, the null hypothesis, that a unit root exists, is rejected. Both do not have unit roots with sufficient significance in their first difference. That means, that both time series are I(1) time series.

The unit root test is executed by using the Augmented Dickey-Fuller Test.

According to the proof, that both are I(1) time series, the time series the required conditions are fulfilled to execute a cointegration analysis.

TFP and EFF are used to create an vector autoregression (VAR) model of the two variables.
The lag order is checked with the lag length criteria. For both variables the lag length of three is sufficient for the further analysis.
In the next step the Johansen Cointegration Test is executed Johansen et al. (2000).

The Johansen Cointegration tests the the null hypothesis, H_0: no cointegration relation.
The null hypothesis is accepted for both cases, i. e. no cointegration relation and at most one cointegration relation. Since the null hypothesis is accepted in both cases, there is no cointegration relation between the two time series. The analysis did not offer any explanation for a connection between the development of TFP and EFF.

The procedure is repeated by using different deterministic trend assumptions for the Johansen test.

A simple linear regression is not enough to show a correlation between the two variables.
Due to the spurious regression problem, it has to be examined, that there is no correlation proved in the analysis, that is not existing and its significance is only caused by the trend in the time serie.
First, the order of integration of the time series has to be determined. Therefore the unit root test is executed. The results for the unit root test can be seen in Table 4.1.

With the Augmented Dickey Fuller test, one possibility to check for unit roots, the existence of unit roots for both the TFP and the EFF time series are shown with sufficient probability.
Taking the first difference of both time series, and check again for unit roots, the result shows that there is no unit root.

Both time series, the TFP and the EFF are first order time series. That means, that the first derivative of the time series is stationary. Due to the fact, that both time series have the same order, a cointegration analysis can be executed.

For the Johansen Cointegration test, the assumptions of 'a linear deterministic trend in data is allowed' and an intercept, but no trend is used.
Other assumptions are tested as well, to check for possible cointegration.
However, the assumptions of an 'a linear deterministic trend, an intercept and a trend' as well as the assumption 'without a deterministic trend and an intercept, but no trend' do not lead to positive results.
The results of the Johansen cointegration test are shown in Table 4.2.

Table 4.1: Output Results of Unit Root Tests

	EFF Level	TFP Level	EFF first difference	TFP first difference
T statistics	-1.7496	-1.5321	-6.9380	-3.7437
Probability	71.18 %	80.27 %	0.00 %	0.04 %
Test critical values:	1 % level	-4.18	1 % level	-2.62
	5 % level	-3.52	5 % level	-1.95
	10 % level	-3.19	10 % level	-1.61

Table 4.2: Results of Johansen Cointegration Test

A.	Unrestricted Cointegration Rank Test (Trace-Test)				
	Hypothesized No. of CE	Eigenvalue	Trace Statistic	0.05 Critical Value	Probability
1.	No deterministic Trend (intercept, no trend)				
	None	0.225	13.10	20.26	35.58 %
	At most 1	0.062	2.64	9.16	64.99 %
2.	Linear deterministic trend (intercept, no trend)				
	None	0.070	5.10	15.49	79.76 %
	At most 1	0.051	2.13	3.84	14.42 %
3.	Linear deterministic trend (intercept, trend)				
	None	0.265	14.83	25.87	58.89 %
	At most 1	0.053	2.22	12.52	95.33 %
B.	Unrestricted Cointegration Rank Test (Maximum Eigenvalue)				
	Hypothesized No. of CE	Eigenvalue	Max-Eigen Statistic	0.05 Critical Value	Probability
1.	No deterministic Trend (intercept, no trend)				
	None	0.225	10.46	15.89	29.41 %
	At most 1	0.062	2.64	9.16	64.99 %
2.	Linear deterministic trend (intercept, no trend)				
	None	0.070	2.97	14.26	94.86 %
	At most 1	0.051	2.13	3.84	14.42 %
3.	Linear deterministic trend (intercept, trend)				
	None	0.265	12.60	19.39	36.11 %
	At most 1	0.053	2.22	12.52	95.33 %

4.4.2 The Structural Break in Germany

The reunification of Germany provides a special case for the time series. It might occur a structural break in the time series. There are methods to test time series for structural breaks. However, the point in time where it occurred is known. That is why the Chow's Test which determines the point of time of a structural break is not applied.

Since the cointegration analysis in subsection 4.4.1 does not lead to a conclusion, the process is repeated considering the structural break.

Due to the issue that there was the structural break in Germany with the reunification of 1990, the methods proposed by Joyeux (2007), Perron (1989), Perron and Vogelsang (1993) and Johansen et al. (2000) are applied.

The process is similar to the one described above, without structural break.

The time serie is split up into two parts. Both time series for TFP and EFF are represented by the time series $Y_{1,t}$ and $Y_{2,t}$ respectively for $t = 1, 2, 3, ..., T = 45$, since the time starts counting with the beginning of the observed time period. The structural break takes place at $t = T_1 = 21$.

Additionally, three dummy variables are introduced in order to model the structural break. According to the methodology described, the variables $t = 1970, 1971, ..., 2014$, $t = 1, 2, ..., 45$, D_2, I_2 and DT^* are introduced (Joyeux, 2007):

$$D_{2,t} = \begin{cases} 0 & \text{for } t \leq T_1 \\ 1 & \text{for } t > T_1 \end{cases} \tag{4.1}$$

$$I_{2,t} = \begin{cases} 1 & \text{for } t = T_1 + 1 \\ 0 & \text{elsewhere} \end{cases} \tag{4.2}$$

$$DT^* = \begin{cases} 0 & \text{for } t \leq T_1 \\ t & \text{for } t > T_1 \end{cases} \tag{4.3}$$

These dummy variables are used as exogenous variables in the statistic software EViews. As described above the analysis is executed in the same way as without structural break.

In order to interpret the results of the Augmented Dickey-Fuller Test (ADF) the ratio λ is needed to look up the correct values in Table 4.3 Perron and Vogelsang (1993).

$$\lambda = \frac{T_1}{T} = \frac{21}{45} = 0.47 \tag{4.4}$$

with T_1 is the year of the structural break and T is the final observation.

After introducing these dummy variables, for the time series, an OLS regression is executed. Therefore a constant term, the linear trend for the whole time period and a linear trend for the time after the structural break is used.

$$TFP = C_1 + C_2 t + C_3 DT^* \tag{4.5}$$

and

$$EFF = C_4 + C_5 t + C_6 DT^* \tag{4.6}$$

The residuals are examined for unit roots.
For the p-test critical values are adapted to the structural break. The values are shown in Table 4.3 (Perron and Vogelsang, 1993).

Table 4.3: Table Perron and Vogelsang (1993)

Percentage Points of the Distribution of $t_{\tilde{\alpha}}$, Model B

λ	T	1.0 %	2.5 %	5.0 %	10.0 %	90.0 %	95.0 %	97.5 %	99.0 %
0.5	50	-4.77	-4.40	-4.09	-3.78	-1.85	-1.60	-1.38	-1.12
	100	-4.57	-4.27	-3.99	-3.69	-1.83	-1.58	-1.36	-1.10
	200	-4.47	-4.17	-3.91	-3.63	-1.80	-1.55	-1.32	-1.03
	1000	-4.48	-4.16	-3.92	-3.64	-1.79	-1.48	-1.20	-0.87
	∞	-4.49	-4.17	-3.93	-3.65	-1.80	-1.47	-1.21	-0.85

The null hypothesis for checking the unit root for Equation 4.5 shows that considering Perron and Vogelsang (1993) table for the p-test, that there is no unit root in the residuals.

After checking the residuals for unit roots, and successfully showing that both do not have unit roots, the cointegration analysis according to JOHANSEN can be carried out.
When creating the VAR model, the exogenous variables are included. These are:
the linear trend t, D_2, $D_2 t$, I_2.

The added variables are included as $D_2(-3)$, $D_2(-3)t$, I_2, $I_2(-1)$, $I_2(-2)$ into the VAR model.
The linear trend is already included by the setting of the Johansen analysis.
That means the trend D_2 is used in the maximum lag order k as well as the trend $D_2 t$.
The variable I_2 is used for the lag orders up to $k-1$.

The VAR model is tested for the lag length according to the lag length criteria.
The lag length is given with $k = 3$.
p is the number of variables for the test. In this analysis we have two variables, $p = 2$, i. e. TFP and EFF.

The VAR model's residuals are tested with the LM and the normality test.

Table 4.4: Output Results of the Johansen Cointegration Test Including the Structural Break

A.	Unrestricted Cointegration Rank Test (Trace)				
	Hypothesized No. of CE	Eigenvalue	Trace Statistic	0.05 Critical Value	Probability
1.	No deterministic Trend (Intercept, no trend)				
	None	0.334	27.75	20.26	0.38 %
	At most 1	0.237	11.06	9.16	2.16 %
2.	Linear deterministic trend (Intercept, no trend)				
	None	0.316	17.37	15.49	2.58 %
	At most 1	0.043	1.82	3.84	17.70 %
3.	Linear deterministic trend (Intercept, Trend)				
	None	0.342	29.27	25.87	1.82 %
	At most 1	0.256	12.12	12.52	5.82 %
B.	Unrestricted Cointegration Rank Test (Maximum Eigenvalue)				
	Hypothesized No. of CE	Eigenvalue	Max-Eigen Statistic	0.05 Critical Value	Probability
1.	No deterministic Trend (Intercept, no trend)				
	None	0.334	16.69	15.89	3.75 %
	At most 1	0.237	11.06	9.16	2.16 %
2.	Linear deterministic trend (Intercept, no trend)				
	None	0.316	15.55	14.26	3.12 %
	At most 1	0.043	1.82	3.84	17.70 %
3.	Linear deterministic trend (Intercept, Trend)				
	None	0.342	17.15	19.39	10.27 %
	At most 1	0.256	12.12	12.52	5.82 %

After that the cointegration test is executed. The results are presented in The results of the cointegration analysis are shown in Table 4.4. The results of the trace test, have to be compared with the critical values, which are given for the structural break in Table 4.5. The values from the critical value table should be considered for the result. The Johansen cointegration analysis does not give a cointegration relation between the two time series.

Table 4.5: Critical Values for Structural Breaks

$p-r$	10.0 %	5.0 %	1.0 %
1	16.76	18.91	23.38
2	34.39	37.35	43.32
3	55.38	59.01	66.22
4	80.05	84.31	92.71
5	108.58	113.48	123.06
6	140.93	146.48	157.26

4.4.3 Germany after the Reunification from 1991 to 2014

After the unsuccessful statistical analysis of the full time series from 1970 to 2014 considering the structural break in Germany in on of the calculation, only the time period after the reunification data from 1991 to 2014 was considered.

Both time series are tested for unit roots. Both are I(1) time series, so that a cointegration analysis can be executed. The unit root results are shown in

Taking the Augmented Dickey-Fuller Test to determine the unit roots, both time series have unit roots. When considering the assumption that the series does neither have a trend nor an intercept, the is shown

Table 4.6: Output Results of Unit Root Tests for Short Time Series

	EFF	TFP	EFF first difference	TFP first difference
T-statistics	1.3586	1.8081	-5.2985	-4.2371
Probability	95.15 %	97.95 %	0.00 %	0.00 %
Test critical values:	1 % level	-2.67	1 % level	-2.67
	5 % level	-1.96	5 % level	-1.96
	10 % level	-1.61	10 % level	-1.61

with high significance, that there is a unit root. Assuming a trend and an intercept gives still sufficient, but way lower, probability for a unit root.
Therefore, the time series can be checked for cointegration. Running the Johansen cointegration analysis does not deliver a correlation relationship between the two variables.

4.4.4 Conclusion of the Statistical Analysis

The link between total factor productivity and aggregate efficiency from the visual point of view could not be confirmed by a statistical analysis. None of the three ways presented to find a correlation gives a positive output. Neglecting the structural break delivered the worst results in regard to the correlation probability. Looking at Figure 4.5 shows already that it should not be neglected.
The structural break in 1990 which has a significant impact in 1991, does not provide a statistical proof of cointegration relation, either.

In both cases the analysis without the structural break and the analysis with including the structural break do not give a statistical correlation. The short time series examined which considers only the time after the reunification does not give reasonable results. The correlation cannot be shown for the case of Germany. That can have the reason in either the quality of data or the length of the time series. However, according to the curves and the ratio of TFP and aggregate efficiency in figure Figure 4.5 the constant ratio applies for the years from 1991 onwards.

The reason why the correlation cannot be shown in the short time series might be that there are not enough sample points to make a significant statement.

Considering the fact, that the outcome of the statistical analysis is not reliable, the ratio between TFP and EFF is used to calculate the further scenarios. The assumption of the constant rate of TFP and EFF is a suitable base for the development of the scenarios.

The finding from Ayres, Warr, that the total factor productivity can be explained by the increase of aggregate efficiency of a company cannot be confirmed statistically for Germany.

The data analysed does not show a correlation between aggregate efficiency and total factor productivity in the time period of 1970 and 2014. However, the curves of total factor productivity and aggregate efficiency follow a similar trend, that can is shown by the ratio of the two variables.

Based on the results of the data analysis, there cannot be done a statement about the long term trend considering the whole industrialisation process of Germany. Thus, only the short-term trend can be observed. For the scenarios in the next step, the average ratio obtained by the time series from 1991 to 2014 are considered.

Chapter 5

Future Scenarios for 2030

In this chapter the findings of chapter 4 are taken to derive scenarios for the years up to 2030. Scenarios are presented to give possible developments for the future. In contrast to forecasts scenarios are not the effort to predict the future. They rather show possible development paths that are based on the application of the economic growth model.

5.1 Scenarios for the Transportation Sector

As shown in chapter 4 the transportation sector contributes to one fourth of the final exergy consumption. The second law efficiency is below the aggregate efficiency of the economy. Thus, it has a high potential of increase in second law efficiency. Combined with the existing targets from Germany's government for the transportation sector, this sector is taken as the reason to consider this sector in the future scenarios.

The focus within the transportation sector is the further development of technology use in transportation.

Due to the change in technology the efficiency and the exergy factor according to the energy carrier used change. Both the final exergy and the final energy values are decreasing. For the two electric vehicle scenarios the final exergy and useful work consumption are presented in Figure 5.1.

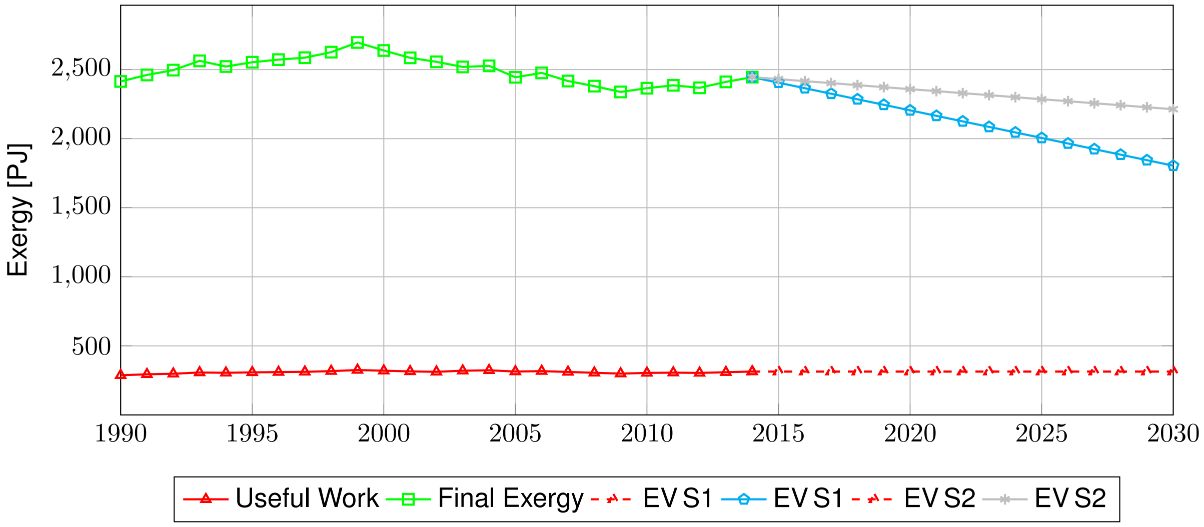

Figure 5.1: Scenarios for Useful Work and Final Exergy Consumption in the Transportation Sector

Electric vehicles have a higher second law efficiency than diesel and gasoline vehicles. That is why the total second law efficiency increases. The increase affects as well the aggregate efficiency. The development of final exergy is decreasing in both cases at a rate that depends on the growth rate of the number of electrical vehicles. Due to the high second law efficiency of electric vehicle, the change in technology used for transportation drives the development of decreasing final exergy consumption.

The amount of final exergy decreases in the scenario with the high increase of electric vehicles to 82 % in year 2030 of the value of the initial year 2014. In the scenario with a moderate increase of electric vehicles the decrease is to 94 % of the initial value.

In order to determine values for the entire economy, assumptions are considered in other sectors. For the sectors industry, energy industry own use and others, the recent trend is assumed to be followed up to 2030. The second law efficiency of the sectors is assumed to follow the trend from the historical data.

In chapter 4 a way to determine the total factor productivity from the aggregate efficiency has been examined.

Based on that assumption, the aggregate efficiency of the economy is determined.

The constant trend of the ratio between total factor productivity and aggregate efficiency is used to extrapolate the total factor productivity from the scenarios for final exergy and useful work.

The scenarios are presented in Figure 5.2.

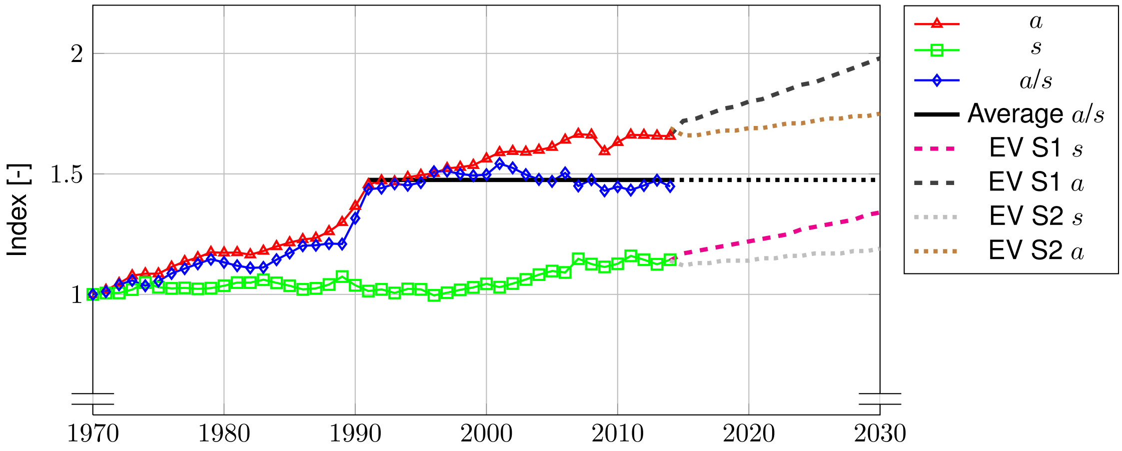

Figure 5.2: Scenarios of Aggregate Efficiency Index and Total Factor Productivity Index Trend

Using the resulting total factor productivity to apply the Cobb-Douglas function gives the result in economic output. As described in chapter 3 two different assumptions are taken to determine capital and labour for the economic model. In scenario EV S1 the assumption of a higher immigration is used whereas in scenario EV S2 the assumption of a lower immigration is used for the calculation.

Two different assumptions for the capital stock are used as described in chapter 3. The indexed values for the economic output and the contribution of capital and labour are presented for both scenarios in Figure 5.3.

EV S1 has a the higher increasing trend of economic output. With these assumptions an output growth rate of 1.5 % can be obtained in 2020 which slightly decreases to 0.9 % in 2030.

EV S2 with a lower increase in aggregate efficiency has a lower growth rate in economic output. The growth rate will reach only 1.0 % in year 2020 which will even decrease to 0.4 % in year 2030.

Seen in Figure 5.3 the contribution of total factor productivity to GDP is high.

The main parameters, that are necessary according to the presented economic growth model are capital, labour and the residual that is described as the total factor productivity.

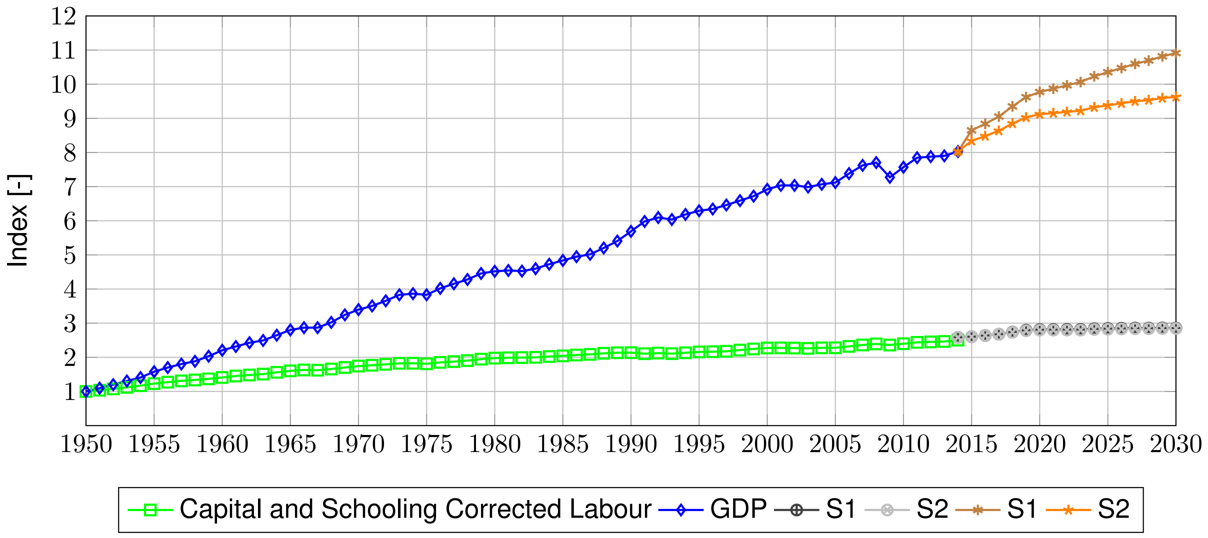

Figure 5.3: Contribution of Capital and Labour to Gross Domestic Product - Scenarios

The scenarios considering only the contribution of capital and labour as factors of production, show a similar trend for the years up to 2030. Even though in the scenarios different assumption about the population is included.

For the population there are two different scenarios assumed. The first one is based on a low immigration, the second one assumes a higher immigration.

However, the scenario of lower immigration and the associated decrease of persons engaged needs to be compensated by a higher number of annual hours worked per person.

It is shown here that the increase of aggregate efficiency is necessary for the economy to grow. It is not only the savings in energy demand that can be obtained that ensure a reduction in energy costs, it is also the change to a new technology that is capable to provide economic growth.

5.2 Scenarios for the Electricity Production

The shares are visualised in Figure 5.4 and Figure 5.5. The results are presented in the overview Table 5.1.

The development of the electricity generation sector is considered to model the change that is driven by the energy transition.

For the scenarios the physical energy content method is used to convert renewable energy final use into primary energy values which accounts one unit of electricity production to one unit of primary energy supply.

The primary energy factor for the energy mix improves from 2.1 in 2014 to 1.69 in 2030 when achieving the target and from 2.1 to 1.92 when the targets are not reached.

The share of electrical vehicle is not high enough to cause a significant impact on the primary energy demand. In Table 5.1 the primary energy demand in both electricity scenarios is presented.

In the first place an electrification helps to increase the efficiency in the transportation sector. The calculation of the primary energy from renewable energies varies depending on the calculation measure that is used. Therefore, the higher the share of renewable energy carrier the more questionable the numbers of primary energy consumption gets because of different existing accounting methods which are described in section 3.4 (Esser and Sensfuss, 2016).

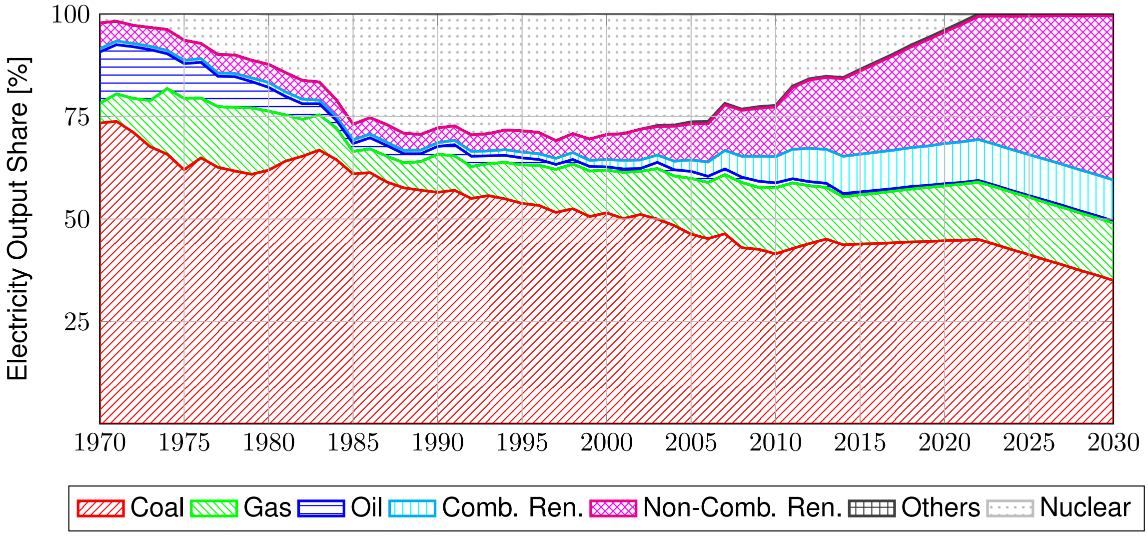

Figure 5.4: Energy Carrier Share in Electricity Generation when Reaching Goals

Coal and natural gas have to replace the lacking nuclear power plant electricity production. In this scenario a stagnation in the expansion of renewable energies is assumed so that the share of renewable energies remains constant.

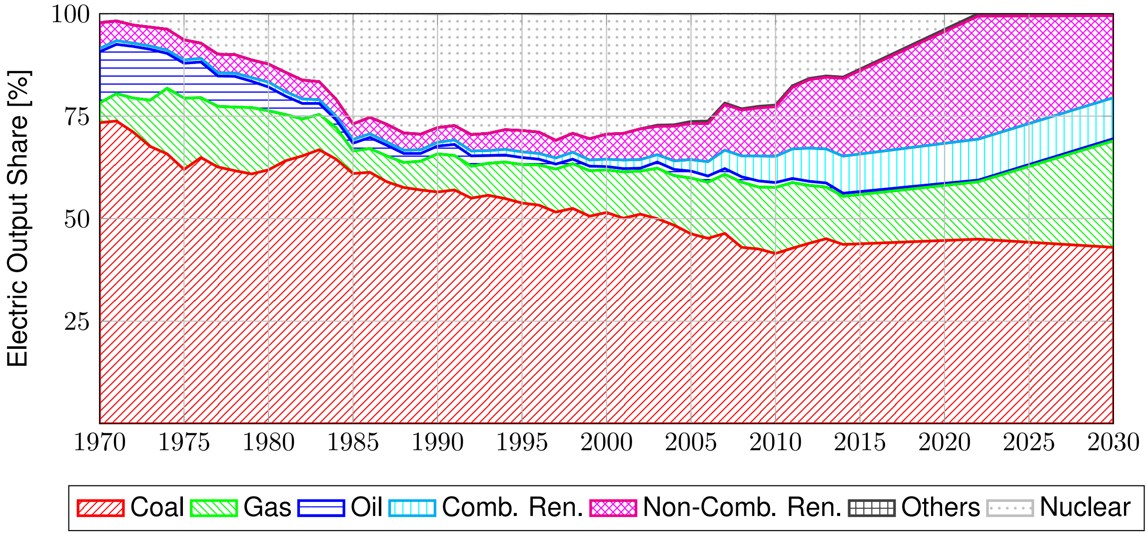

Figure 5.5: Energy Carrier Share in Electricity Generation when Failing to Reach Goals

5.3 Analysis of the Scenarios

The optimistic scenario provides an idea, how the intended development of the German government looks like in regard to useful work consumption and aggregate efficiency. An increase in aggregate efficiency is reached due to the fact, that the major technology that is used in the transportation sector is step by step replaced by another technology.

The second scenario provided describes the development of a slow increase of electric vehicles in Germany.

However, the application of the economic model only considers the technological change and the involved increase of aggregate efficiency. It does not consider the development of the international

Table 5.1: Four Future Scenarios for Germany in Year 2030

		EV S1			EV S2		
	2014	2020	2025	2030	2020	2025	2030
Population (N_p)	80.65	81.95	81.59	80.92	81.43	80.51	79.23
Employed people (N_e)	42.45	46.24	44.66	42.59	45.85	43.88	41.42
Labour [x10^9 h]	58.2	62.9	61.0	58.8	62.4	59.9	57.1
Labour$_{\text{corr}}$ [x10^9 h]	213.2	230.4	223.3	215.3	228.4	219.4	209.4
Capital (K) [x10^9 2011€]	9,983	11,000	12,075	13,149	10,994	12,230	13,691
Transportation:							
Useful Work (U) [PJ]	314	314	314	314	314	314	314
Final exergy (B) [PJ]	2,445	2,205	2,005	1,804	2,358	2,285	2,213
Final Energy (E_F) [PJ]	2,310	2,086	1,899	1,712	2,229	2,161	2,093
Primary energy (EL1) [PJ]	2,541	2,328	2,140	1,946	2,465	2,398	2,328
Primary energy (EL2) [PJ]	2,541	2,328	2,147	1,972	2,465	2,400	2,330
Aggregate efficiency [%]	12.82	14.23	15.65	17.39	13.30	13.73	14.18
TFP (A) [-]	3.33	3.61	3.79	3.97	3.39	3.46	3.52
TFP index (a) [-]	1.66	1.80	1.88	1.98	1.69	1.72	1.75
Q [x10^9 2011€]	2,637.5	3,112.3	3,297.2	3,475.1	2,904.6	2,987.7	3,066.8
Q growth r. [%]	1.90	1.57	1.18	0.89	1.04	0.62	0.37

market in the sector of transportation. The major share of the passenger car stock in Germany is produced by German companies. The model excludes the fact, that the production of the new passenger vehicles can be either done by German companies or by international competition. That decides if the value of the products purchased is added to German GDP or not.

Chapter 6

Conclusion

In the process of finding a solution on how to deal with climate change, the focus is increasingly the compatibility of technological change with environmental and economic goals. The energy sector plays a significant role in the technological change. Policy designs that intend to accelerate the change to the use of more environmentally friendly technologies needs to consider their impact on the economy. Economic models are necessary to understand the link between change in technology and economic growth. However, the neoclassical economic growth model is not sufficient to describe the technological progress, as technological progress is only included in this model as an exogenous driver. Therefore, a modified model with technological progress endogenised is required.

The exergy-economic model was used in this thesis to examine the link between energy demand and economic growth in Germany. This model allowed the comparison of different technologies, at the same time, regarding their efficiency. For this comparison, an energy metrics that allows putting all forms of energy into the same scale was used: exergy. In contrast to the measure of energy, the exergy approach allowed an estimation of which amount of thermodynamic work is necessary to obtain the desired energy service and to which extend the available energy is used. It has been shown that the final to useful aggregate exergy efficiency that describes the overall thermodynamic efficiency of an economy is linked to the total factor productivity which contributes to economic output. The present research showed that the exergy-economic model that has been used for Portugal in the project MEET2030 can be used for Germany's economy.
A short-term data analysis was executed to examine the link between final to useful aggregate exergy efficiency and total factor productivity for the time period from 1970 to 2014. The data analysis included an evaluation of both macroeconomic and exergy consumption data. The useful step of the exergy flow provides a measure of the amount of useful work needed to keep the economic process running and growing. The analysis of historical data has been used to find the trends in the development of final to useful aggregate exergy efficiency and total factor productivity and has been used as a base to develop scenarios for the future.
The statistical analysis did not provide a significant correlation between the measure of aggregate efficiency and the total factor productivity. However, the constant ratio of the two measures after the reunification of Germany suggested a trend which was continued for the near future.

The scenarios presented in chapter 5 show that the economic growth will go along with the increase in aggregate efficiency of the economy. The population number has a decreasing trend and the average age of population is increasing so that labour as a factor of production will contribute less to economic output when a constant total number of annual hours worked per person is assumed. Therefore, the technological progress has to compensate the decrease of labour if the number of total annual hours worked remains at the recent level.

In this thesis, mainly the individual road transportation sector is examined. That sector has a potential to increase the aggregate efficiency up to 25.8 % in year 2030.
This increase of the second law efficiency needs to be realised by the change of technology that is used for the transportation energy service. Considering the optimistic scenario presented with an share of one third of electric vehicles in Germany by 2030 leads to the model to an increase of aggregate efficiency of 3 % compared to today. The economic growth in this scenario remains at a level of 2 % in the next years and decreases to 1 % by 2030.
Electricity is currently responsible for one fourth of the final exergy demand, whereas it provides around 45 % of useful work consumption. That can be attributed to the high second law efficiency of electricity, that can be usually converted into 100 % useful work. However, still losses occur depending on the technology.
The development in the electricity sector is focused on increasing the share of electricity provided by renewable energy carriers. The goal is the reduction of GHG emissions in the electricity production. There are targets for the share of electricity provided by renewable energies and the reduction of GHG emissions. Another major change is the the nuclear phaseout by 2022 which has been decided by the German government. The power plants which will be shut down have to be replaced by another technology.
Depending on the assumption about the growth rate of renewable electricity generation, the nuclear energy carrier has to be replaced by other conventional energy carriers, i. e. coal or natural gas. Over time, coal can be replaced by renewable energy sources. In the first place, that would result in an increase of carbon dioxide gas exhausts in the short run. For the long run the reduction of GHG emissions can be ensured at the point when non-combustible renewable energies replace the conventional energy carriers.

This thesis has presented a model of the German economy that includes energy by using the exergy measure. The model is able to examine the impact of technological change in regard to the economic output. The aspect of energy has been endogenised into the economic growth model. It has been used to derive conclusions about the future pathway of the individual road transportation sector in Germany.

In the next step it can be applied for the other sectors which have not been examined in this thesis yet. Especially the residential sector shows potential for an increase in efficiency. However, the real estate sector is changing slower than the transportation sector due to the high lifetime of buildings. By providing the scenarios the model can be used as a base for argumentation for policy design in order to guide the development towards a thermodynamic more efficient economy. The focus of the future development needs to be on the increase in aggregate efficiency of the German economy to ensure economic growth. It has to be examined, how the aggregate efficiency of a country can be improved by maintaining the economic structure in the country.

For each economic sector the European Commission (2018a) provides data about the best technology available on the market. Scenarios needs to be developed that consider these best technologies available to examine which improvement of the aggregate efficiency can be obtained by replacing currently used technology in order to determine the potential of the technological change. Policies need to target the increase of aggregate efficiency for Germany. The availability of data has to be improved to make the analysis more reliable and more detailed.

According to the results of the model it can be assumed that the useful work can be maintained constant while economic growth is ensured. In the next steps it has to be examined, to which extend the reduction of useful work intensity is due to the fact of the shift of the German economy to a service economy. Assuming for the development of the next years until 2030 that the amount of useful work is constant it can be backwards be determined what aggregate efficiency has to be reached in order to achieve the climate goals, the goals for the reduction of GHG emissions and the goals for renewable energies. The recent trend towards a sharing economy might cause a decrease in useful work consumption in the future. The reason for a reduction in useful work consumption may be optimisation measures regarding the use of assets. The effect of a reduction in useful work needs to be studied on the effect on the economy. The next step can be to apply the tool for a specific policy that is developed and check the behaviour of the economy when the policy is applied.

Appendix A

Supplementary Graphs and Tables

A.1 Macroeconomic Examination

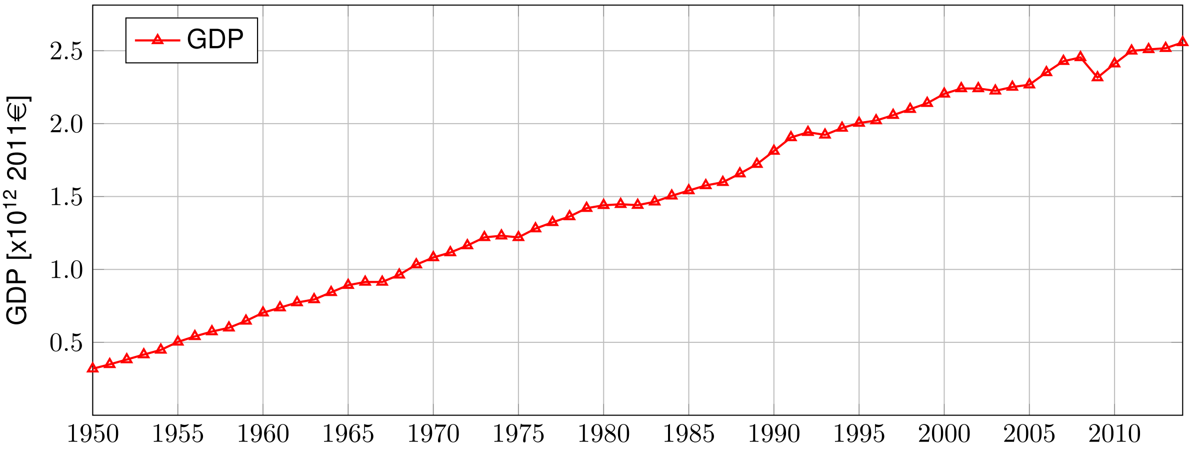

Figure A.1: Gross Domestic Product in Germany from 1950 to 2014

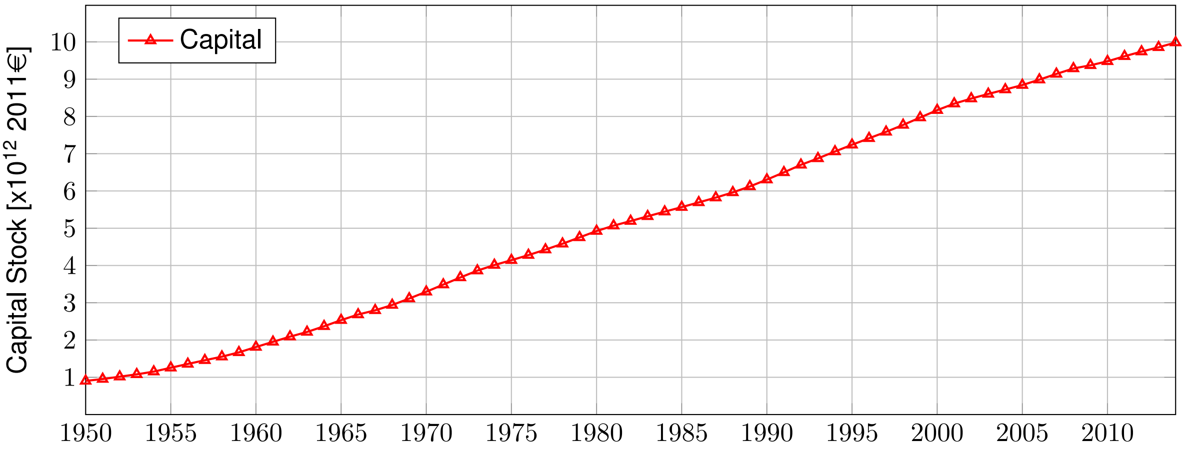

Figure A.2: Capital Stock in Germany from 1950 to 2014

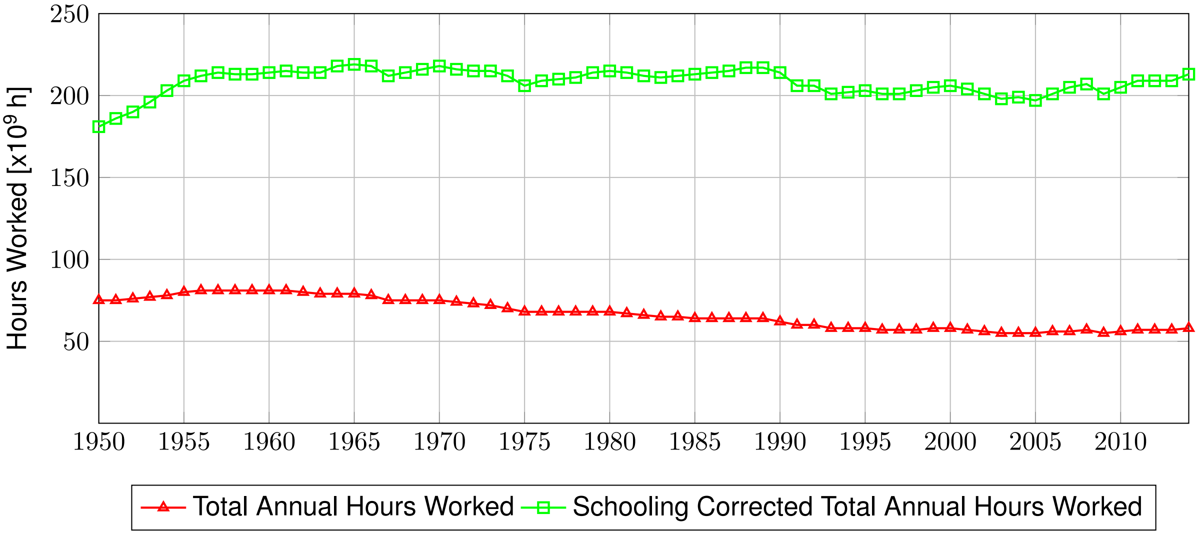

Figure A.3: Labour in Germany from 1950 to 2014

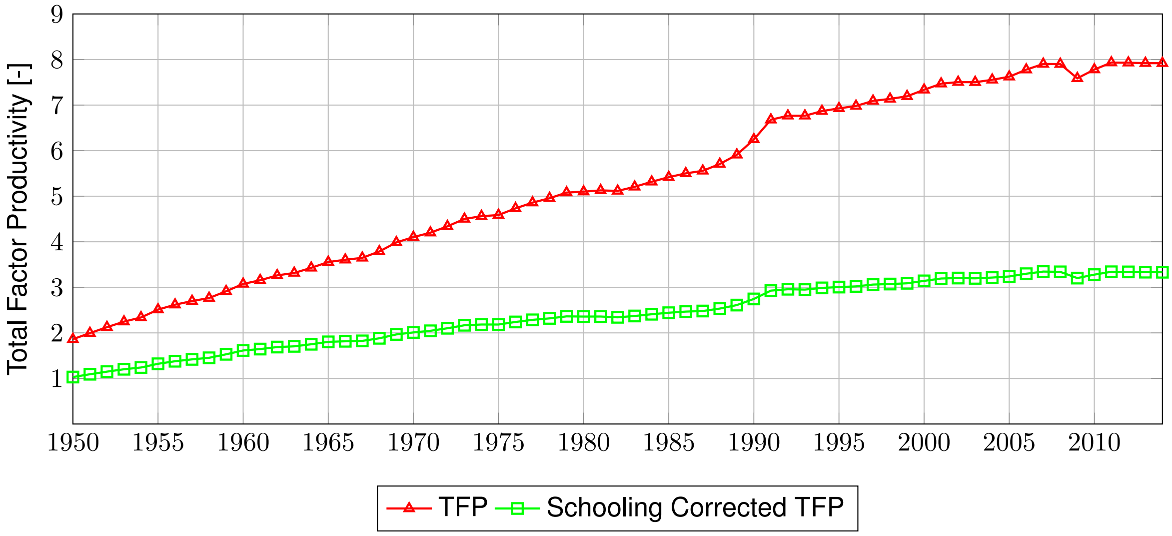

Figure A.4: Total Factor Productivity in Germany from 1950 to 2014

A.2 Exergy Examination

Table A.1: Aggregated and Disaggregated End Use Categories

Disaggregated end use categories	Aggregated end use categories
Fuel – high temperature heat (500 ℃)	High Temperature Heat
Fuel – medium temperature heat (150 ℃)	Medium Temperature Heat
CHP – medium temperature heat (150 ℃)	
Fuel – low temperature heat (120 ℃)	Low Temperature Heat
Fuel – low temperature heat (90 ℃)	
Fuel – low temperature heat (50 ℃)	
CHP – low temperature heat (120 ℃)	
CHP – low temperature heat (90 ℃)	
CHP – low temperature heat (50 ℃)	
Steam locomotives	Mechanical drive
Diesel vehicles	
Gasoline/LPG vehicles	
Aviation	
Navigation	
Natural gas vehicles	
Diesel-electric	
Oil – stationary mechanical drive	
Coal – stationary mechanical drive	
Coal/oil light	Light
Electricity – industry	(treated separately)
Electricity – transport	(treated separately)
Electricity – other sectors	(treated separately)

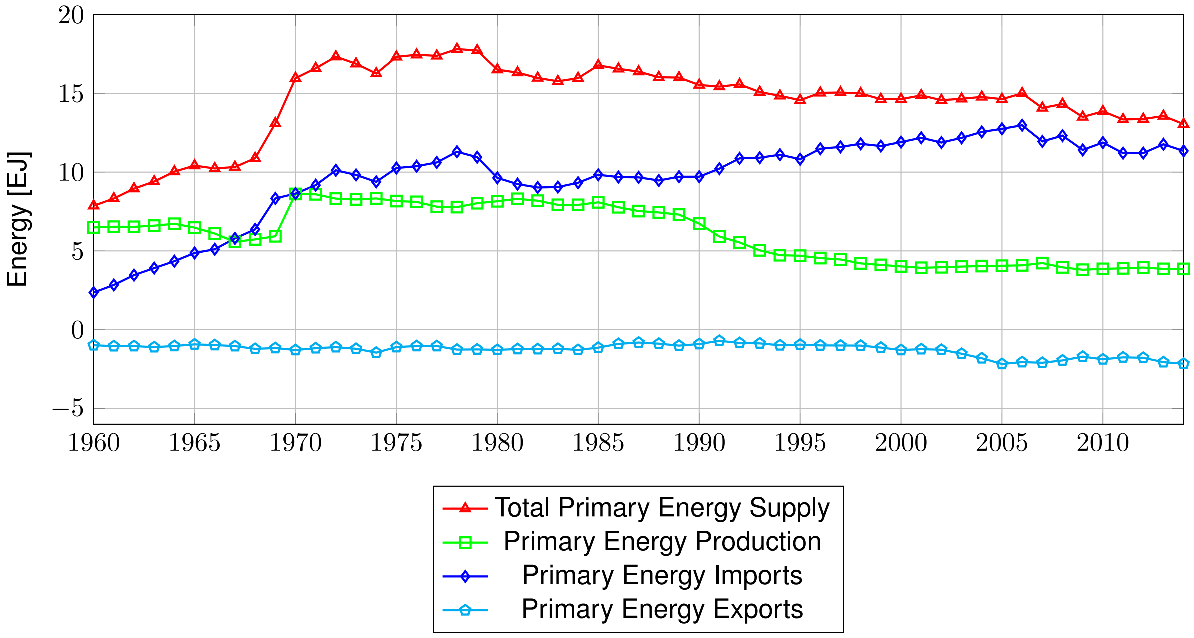

Figure A.5: Total Primary Energy Supply and its Components from 1960 to 2014

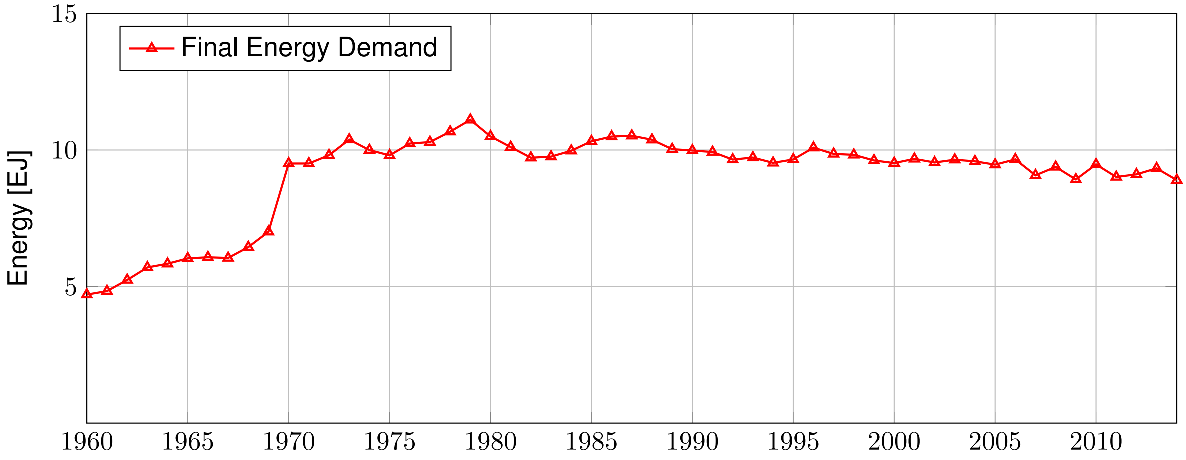

Figure A.6: Final Energy Demand in Germany from 1960 to 2014

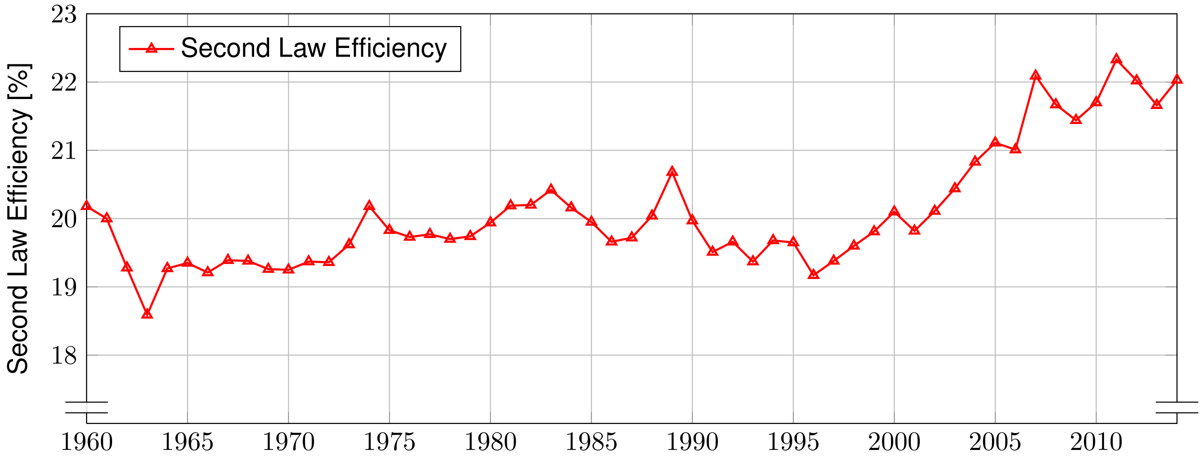

Figure A.7: Aggregate Exergy Efficiency in Germany's Economy

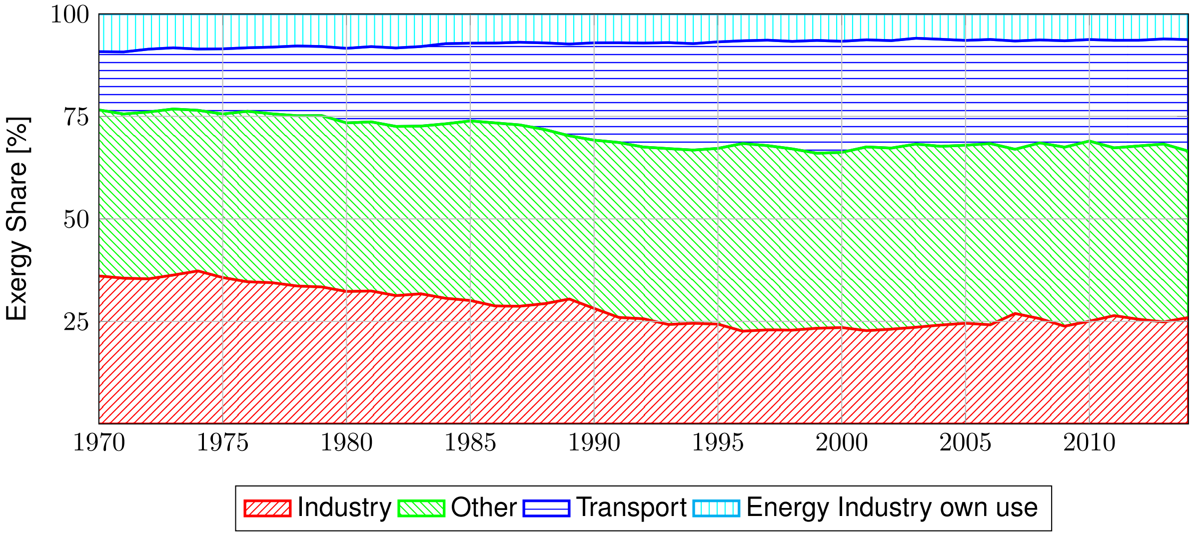

Figure A.8: Share of Final Exergy in Economic Sectors

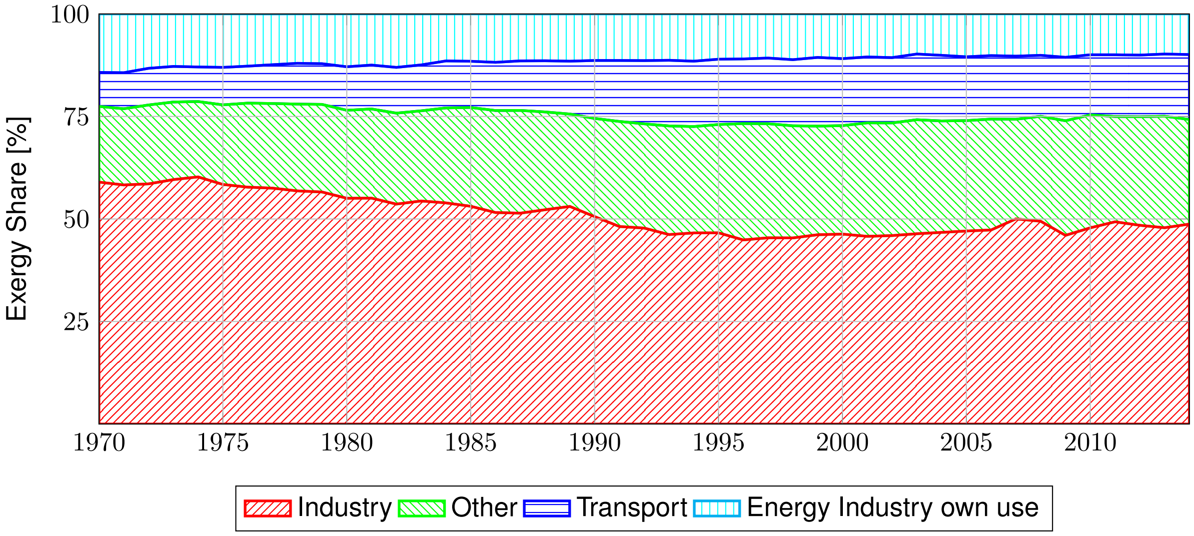

Figure A.9: Share of Useful Work in Economic Sectors

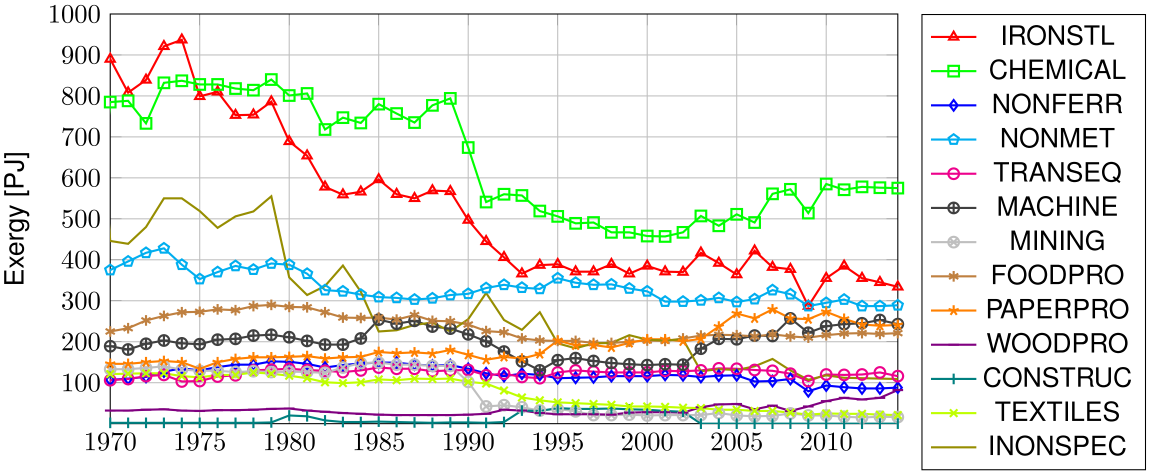

Figure A.10: Final Exergy in Industry Sectors

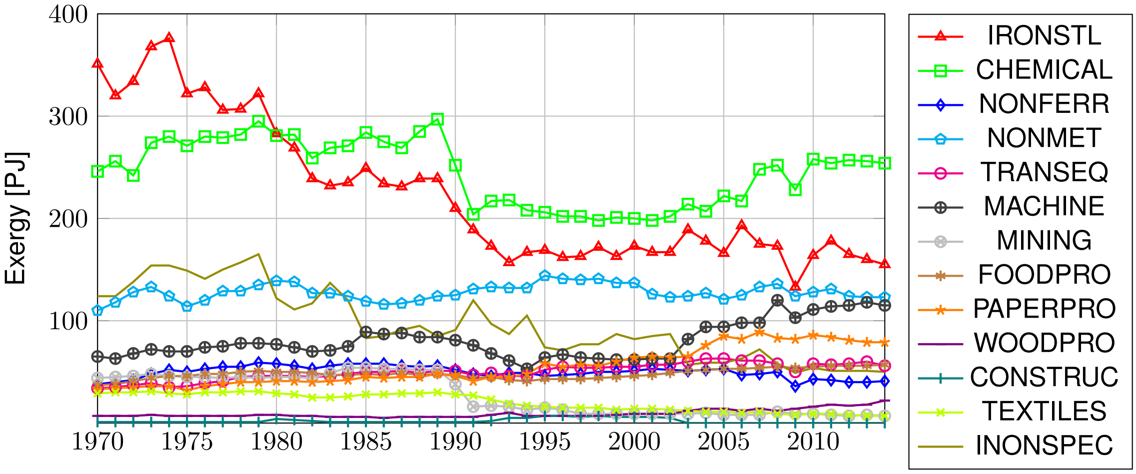

Figure A.11: Useful Work in Industry Sectors

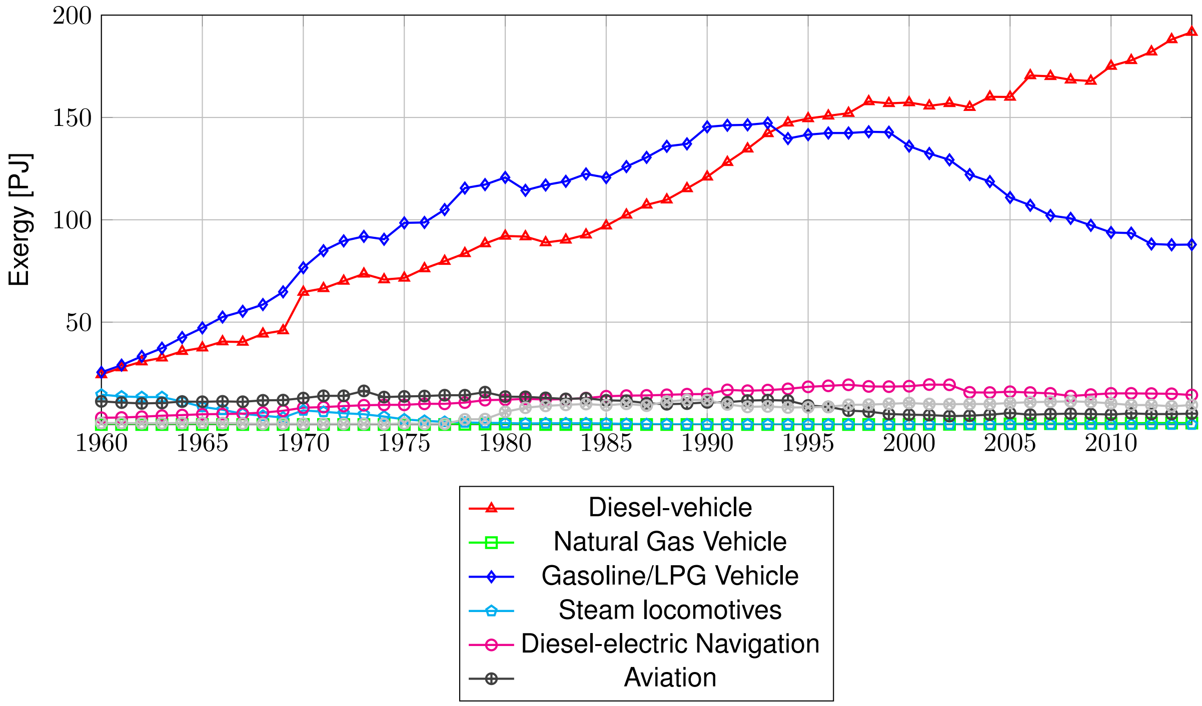

Figure A.12: Useful Work in the Transportation Sector

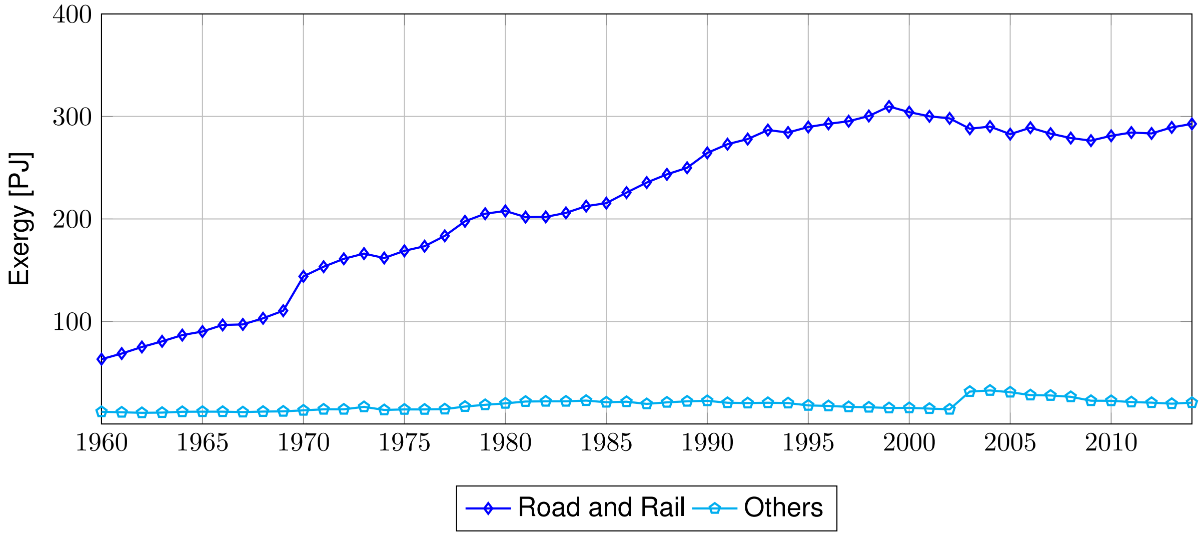

Figure A.13: Useful Work in Transportation: Rail & Road and Others

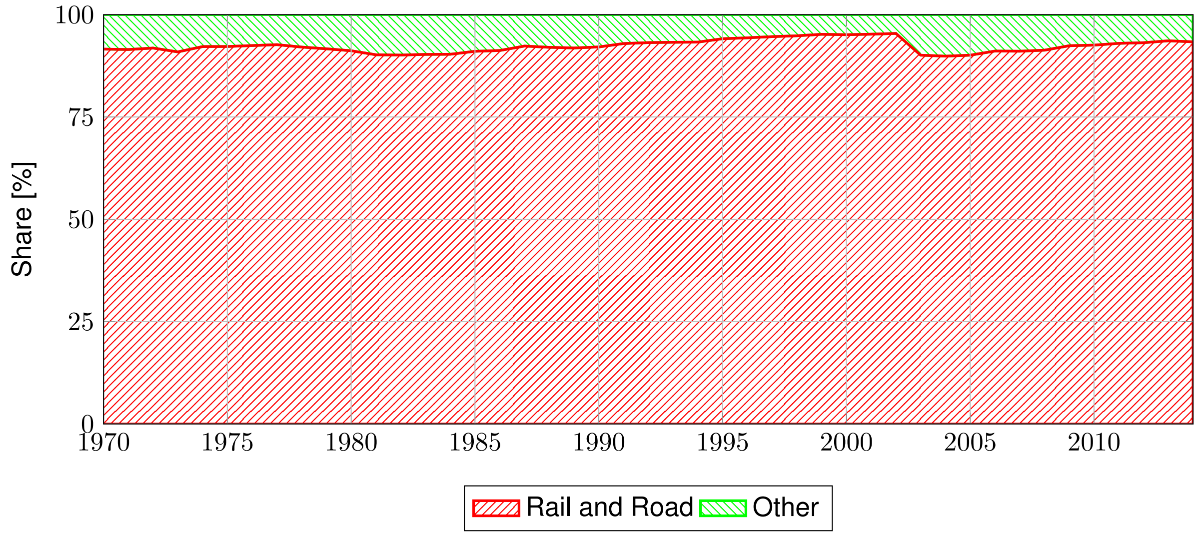

Figure A.14: Shares of Useful Work in Transportation: Rail & Road and Others

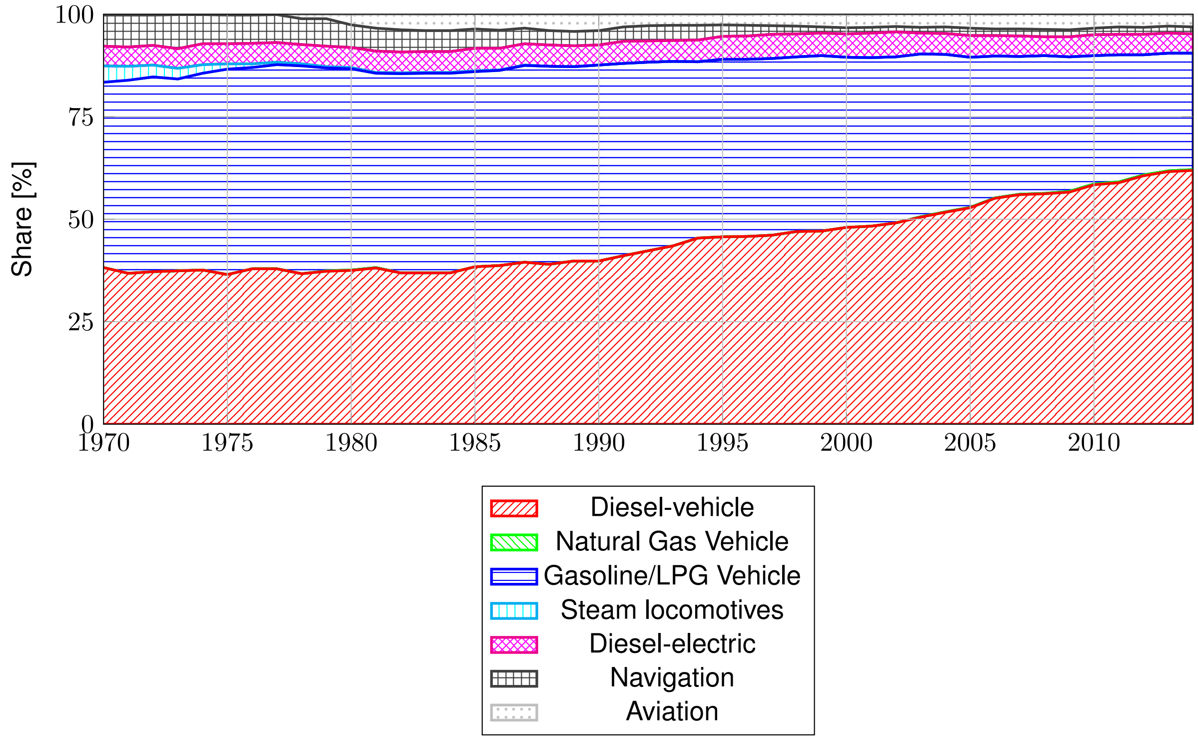

Figure A.15: Shares of Useful Work in Transportation: Disaggregated End Uses

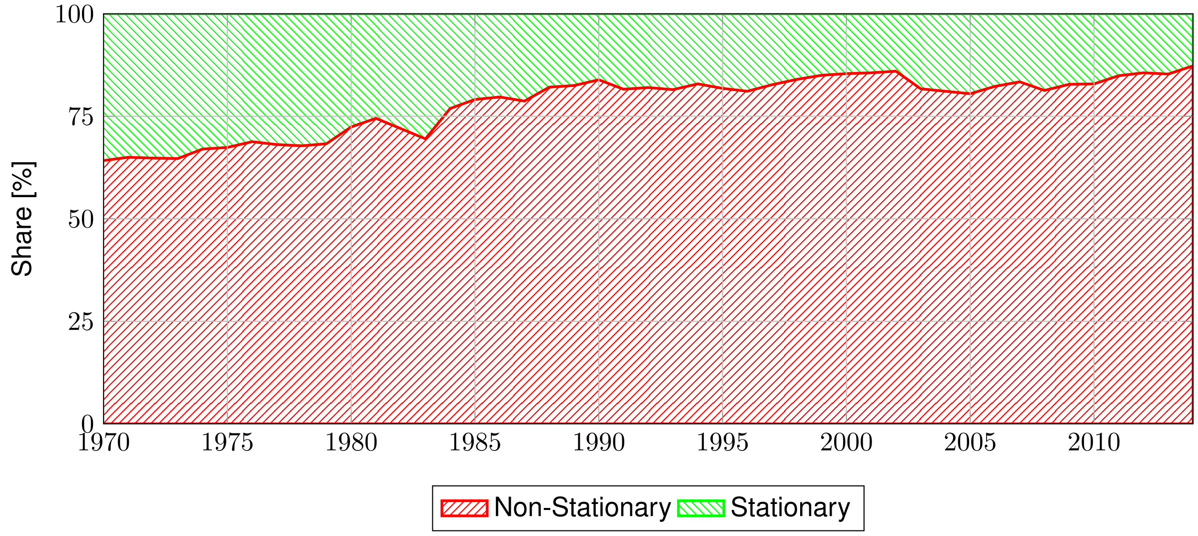

Figure A.16: Shares of Useful Work in Transportation: Stationary and Non-Stationary End Use

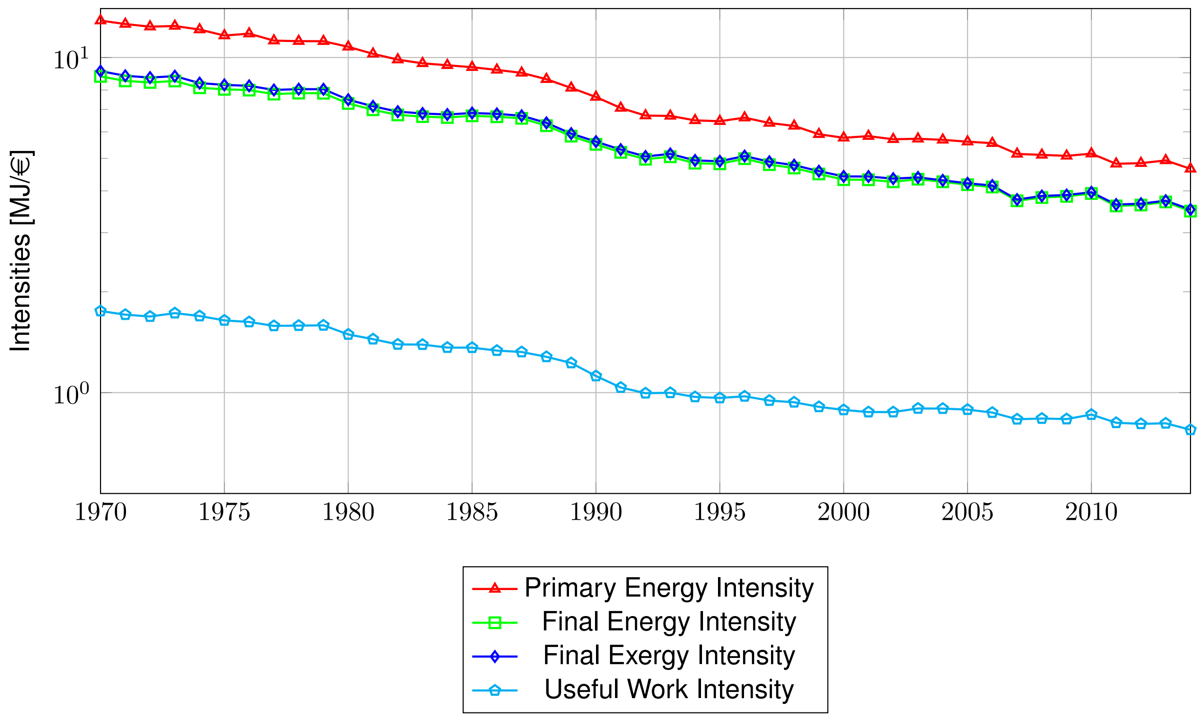

Figure A.17: Energy and Exergy Intensities

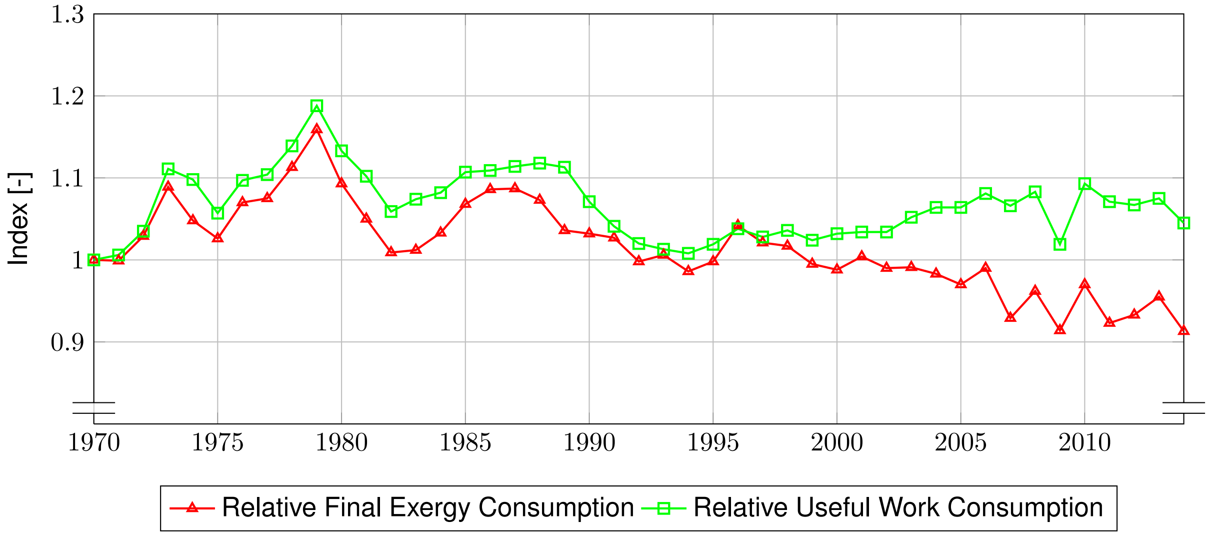

Figure A.18: Relative Development of Final Exergy and Useful Work Consumption

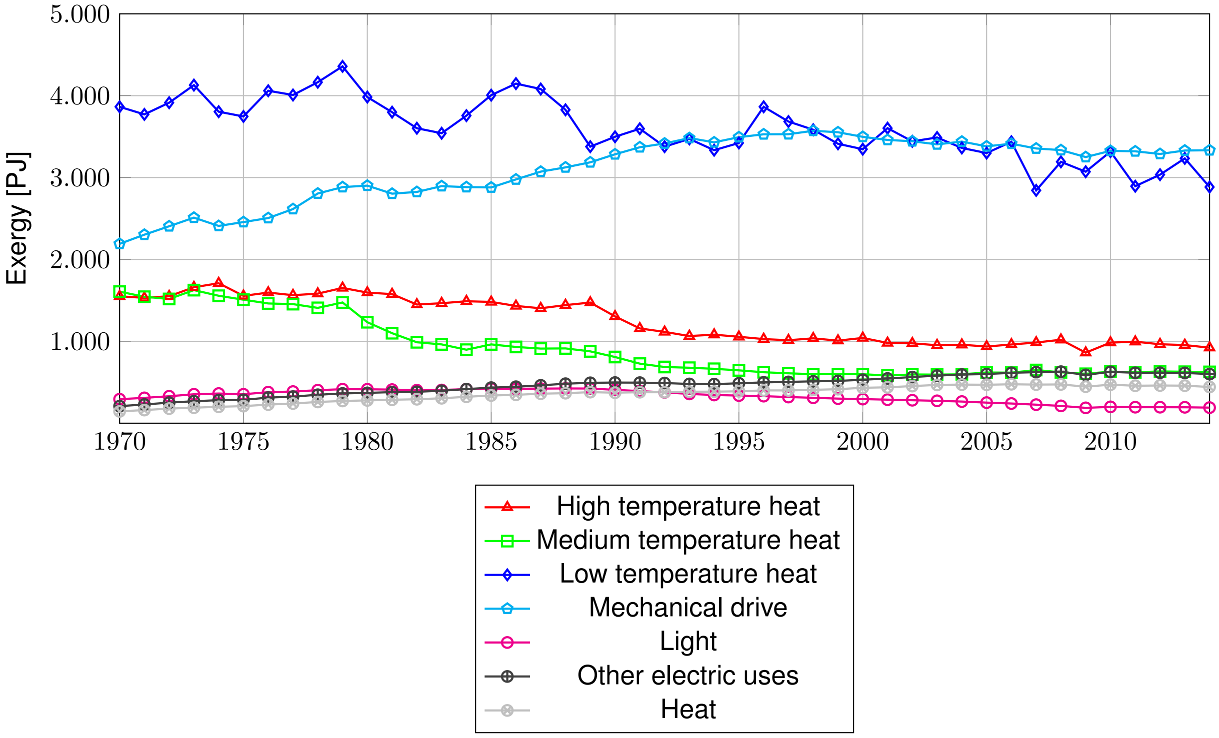

Figure A.19: Final Exergy in Aggregated End Uses

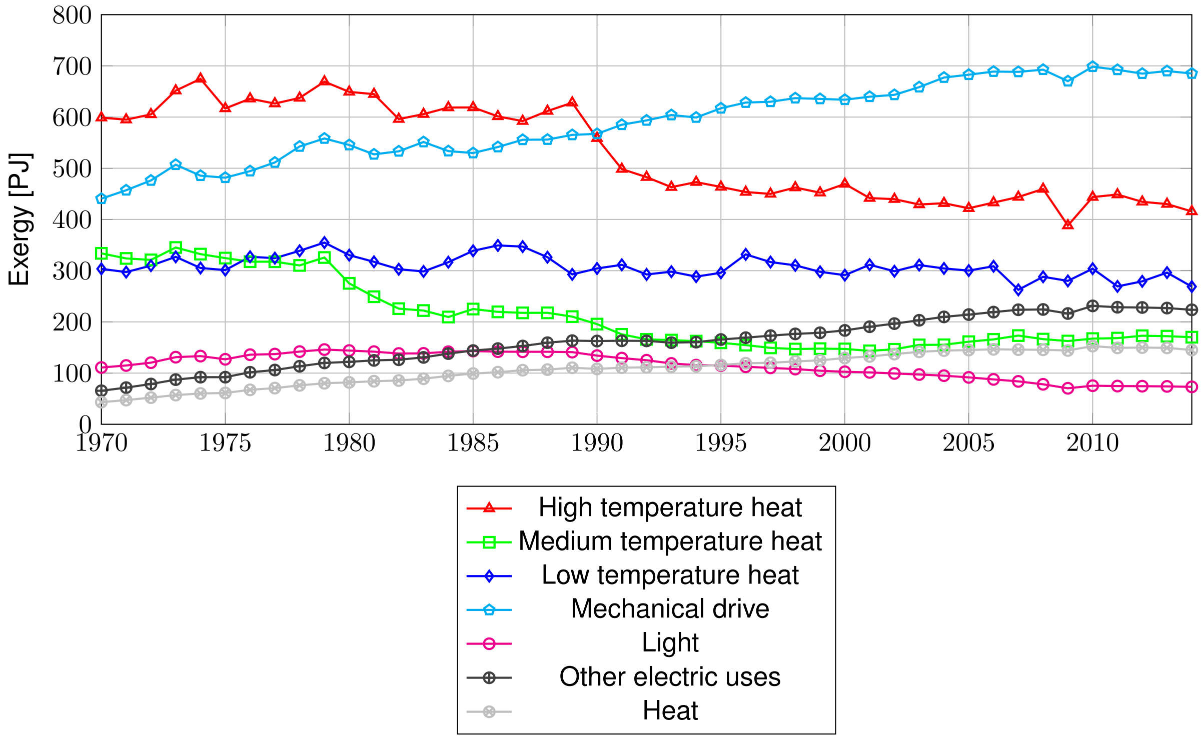

Figure A.20: Useful work in Aggregated End Uses

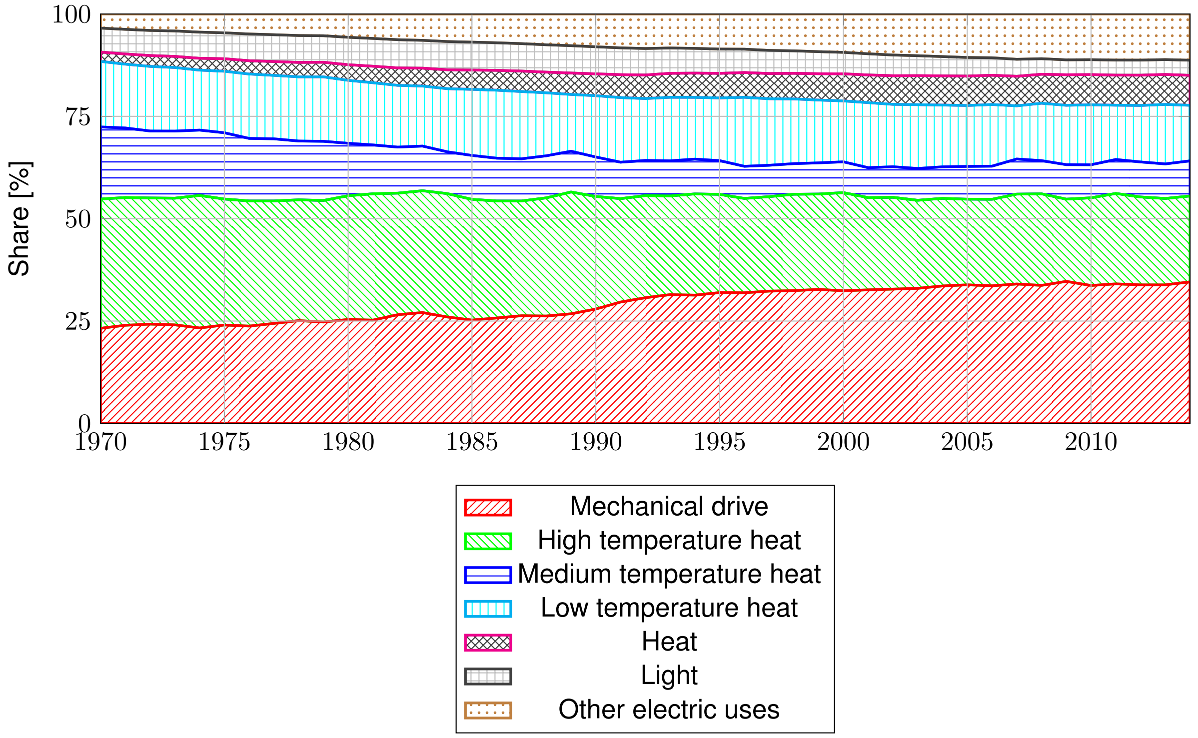

Figure A.21: Shares of Useful Work in Aggregated End Uses

A.3 Future Scenarios

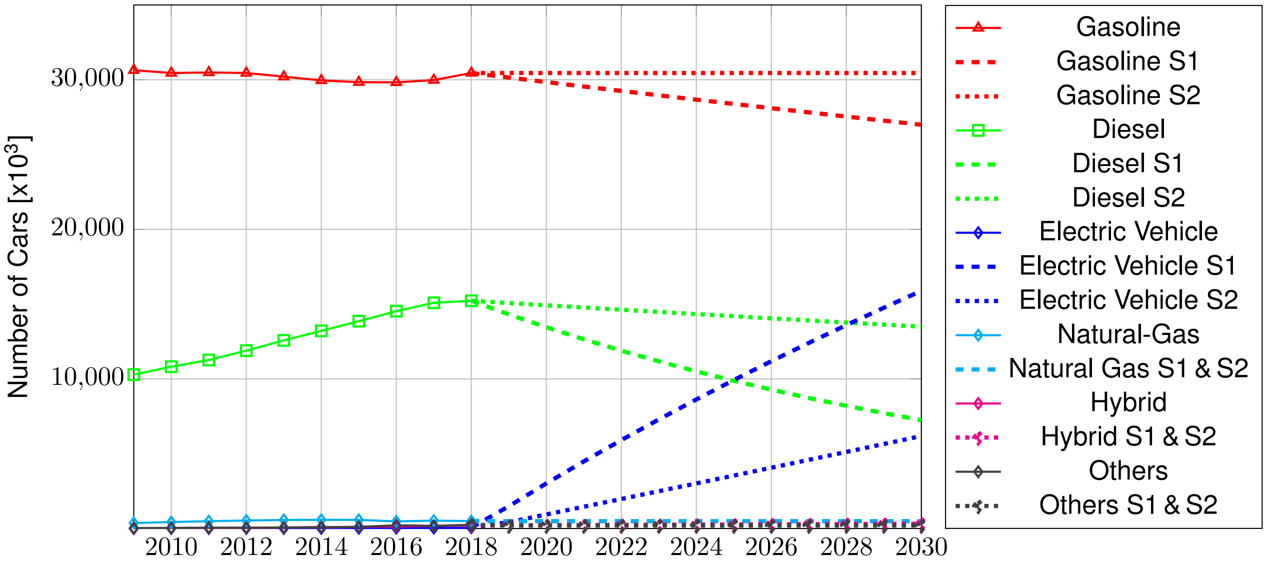

Figure A.22: Scenarios of Car Stock in Germany

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