Germany 2030: Estimation of the Impact of Electrification of Individual Road Transportation Sector in the Economy - An Exergy Economic Analysis

Lucas Schreiner
lucasschreiner@gmx.de

Instituto Superior Técnico, Universidade de Lisboa, Portugal

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

1. Introduction

To ensure wealth for the citizen of a country the economic power needs to be ensured. The industrialisation process shows that energy and economics are closely related to each other. The major impact on the environment occurs due to the use of fossil fuels as energy carrier. That leads to the need of understanding how the economy is affected by a change of energy demand and supply. Besides the environmental aspects, economic ones play a significant role in discussions on the path to follow within a country. The intended growth path is an increase in economic output while avoiding negative effects on the environment. Germany began with the energy transition, which is the process of turning from the use of conventional energy carriers to renewable energy sources. The transition goes along with the increase of electricity production from renewable energy carriers and the nuclear phaseout. Therefore, the use of energy carriers needs to be evaluated regarding the effect on economy and environment. The goal needs to be a prospering economy with the commitment of minimising a negative impact of the economic activity on the environment.

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. 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. That directed the focus increasingly on the local air pollution by cars in city regions and on global scale.

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 which is 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.

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, the model is required to examine possible future pathways.

2. Linking Energy and Economic Growth - the State of the Art

2.1. Economic Growth Theory

On the macroeconomic scale, Robert Solow and Trevor Swan set up an economic growth model for long-run economic growth [17, 18, 19]. 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.Thus, the aggregate production function can be written as [18]:

$$Q = A(t)K^{\alpha}L^{\beta} \tag{1}$$

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. $A(t)$ represents a time dependent multiplier that describes the residual, that is called Solow-residual which is attributed to technological change. As a measure for economic output the gross domestic product (GDP) is used. Technological knowledge is embodied in labour and included into the production function [21].
Natural resources are neglected by the neoclassical economic theory despite their importance for an economy [7]. A real economic system depends on physical material and energy inputs. 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.

2.2. Thermodynamic Definitions

The measure energy is defined as the capacity to do work [8]. Since energy can neither be created nor destroyed, it can be only transformed to different forms [22]. The most important forms are electric energy, chemical energy, kinetic energy, thermal energy, potential energy and electromagnetic 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. [8]. When using this form of energy, the energy is dissipated while using it.
A possible way to evaluate the energy flow is using exergy as a measure. Exergy is the measure of available energy, that is energy capable of performing mechanical, chemical or thermal work [4]. Therefore, the exergy approach can be used to evaluate the quality of energy [8]. 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. In contrast to the energy flow, within an exergy flow a share of the exergy is destroyed in each step of transformation and entropy is created. 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.
The quality of energy, measured by exergy, decreases all along the way from the primary stage of natural resources until the final step which is the desired service.
This measure of useful work describes the amount of exergy that is needed to provide the desired energy service. In the transformation from final exergy to useful work the second law efficiency describes 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.
The second law efficiency is specific for each end-

use and the technology that is used.

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.

2.3. The Exergy Approach

The need of high-quality energy services is a necessary condition for economic growth [8].
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 GDP. The scarcity of energy supply affected the economic output.

In the time period after the Second World War six recessions occurred in Germany [12]. The oil price crisis in 1973 and 1979/80 caused a drop in GDP in most countries. Since the neoclassical model only explains a small fraction of the observed economic growth, it is extended by considering physical material and energy input [5].

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 [3, p. 251]. Energy demand is considered only as a consequence of growth, and not a driver of growth [24]. That is in contradiction to the observation that energy scarcity, that is caused by energy price increase does affect the economy [12].
Instead of the exogenous driver of technological progress two learning processes are included into the model [24]. 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 [25]. 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. Evaluation methods are needed to make a statement about the 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 [25, 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 and technology/natural resources are ignored.
The improvements of efficiency with which fuel exergy is converted into useful work is a significant driver of growth.
Recently it seems, that the economic system depends on the high input of fossil fuels, rather than on considerable efficiency gains. In this paper, no explanation is delivered, 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.

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.

[10] examines the German service industry using the 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 which supports the implementation of a low carbon economy in Portugal. Therefore, macroeconomic and energy data has been analysed in order to examine historical data of useful work consumption in Portugal and pointing out a link between the aggregate efficiency of Portugal and its economic growth. Based on that the project provides scenarios which were developed with experts from science and industry to obtain robust results. The output were two extreme scenarios for Portugal up to 2030. The first includes the optimistic assumptions, the second includes the pessimistic ones for the future development. The scenarios support the decision making processes on the way to a low carbon economy and point out the crucial parameters to focus on.

3. Methodology

3.1. Data Collection and Analysis for Germany

The neoclassical economic growth model is applied for Germany. In the first place, macroeco-

nomic data for capital, labour and GDP is used to apply the economic growth model for Germany. The Cobb-Douglas function is used to determine the contribution of capital and labour weighted according to the labour share and the capital share to the economic output [17, 18]. 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 [6]. For the economic model it is assumed that one third of the generated income of an economy is spent on capital, whereas two third are spent on labour.
Using the data for capital, labour and gross domestic product from PWT 9.0, the macroeconomic data is analysed for Germany.

The economic output is described as the Cobb-Douglas production function which includes the total factor productivity.

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 both production factors is considered as well as the factor shares and the economic output. The economic output Q is measured in monetary values by 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. 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 are corrected with the Human Capital Index (HCI) which allows to compare the productivity of hours worked between different education levels and over time [14].

The Cobb-Douglas function shown in equation 1 is used with the constant shares of $\alpha = \frac{1}{3}$ and $\beta = \frac{2}{3}$. That means, technology quadrupled the productivity of the economy over these years.

3.2. 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 data is presented for all economic sectors of industry, transport, energy industry own use and others, shown by energy carriers. 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.

Primary energy carriers provide the energy directly from natural resources. The embodied energy can be extracted by using a transformation process.
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.

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).

For each year and sector the final exergy and useful work values are determined. With the values for the final exergy and useful work consumption, the aggregate efficiency is calculated [15]. 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.

3.3. The Exergy Economy Model

To connect the findings from the macroeconomic analysis, the final exergy and useful work intensity is determined following the approach presented in [15]. In the next step, the ratio of the annual values of aggregate efficiency and total factor productivity is examined as a possible way to provide an explanation for the total factor productivity.

For Portugal it has been examined, if the total factor productivity can be explained by the increase of aggregate efficiency [1].
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 $s_t = S_t/S_{1970}$).
It is examined, if the finding for Portugal that the trend of total factor productivity is connected to the trend of aggregate efficiency also applies for Ger-

many. The ratio is a suitable way to graphically compare the evolving trend of both time series.

Based on the work of [2] it is examined if the total factor productivity can be endogenised. An increase in thermodynamic efficiency of the economy is related to the measure of total factor productivity [23, p. 4]. The finding that has been made in that work is examined for Germany.

3.4. 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.

The development of the future trends is based on forecasts in literature. Considered are the demographic development [11], the capital stock [20] and the transportation sector, especially its electrification [13]. The remaining sectors like industry, energy industry own use and others are assumed to continue the trend that they show within the recent past. 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.

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 [13].

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. 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 [16].
The numbers of cars in Germany are shown in table 1.

Table 1: 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

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 [16].

In the scenarios the development of electricity consumption and the generation of electricity is based on the national targets and national forecasts. The scenario calculation is done with the optimistic development, that the defined targets are reached. A pessimistic scenario is developed, where the goals are not reached.

Two different scenarios for the electricity production are provided. 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 2 presents the shares of energy carriers used in electricity production in the development over time.

Table 2: 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 %

4. The Link between Exergy and Economic Growth

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 are determined. The production factors are weighted according to their monetary shares. Comparing the result 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. Schooling correction is not sufficient to explain the economic output. 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 1 provides the multiplier that represents the total factor productivity. It is calculated in 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.

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.

4.1. Useful Work for Germany

For the time period from 1970 to 2014 energy data is analysed following the approach used by [15] in order to determine the useful work consumption and the useful work intensity for Germany. 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. 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 [9]. 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. 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 should 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 developed scenarios it is assumed, that the useful work consumption remains constant over time, due to a constant distance travelled per person per year.

4.2. 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 exergy intensity of an economy. The useful work consumption is constant from the 1970s onwards 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 to 0.77 MJ/€ in 2014. The decreasing trend of the intensity is attributed to the increase in GDP.

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.

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 primary energy intensity decreased by two third of the initial value.

4.3. Mechanical Drive as End Use

An increasing trend for useful work consumption in the end use mechanical drive is observed for Germany. That trend is further examined. The share of stationary mechanical drive (in industrial processes, etc.) is small in comparison to the one of non-stationary drive (in transportation). That means, the increase of labour productivity cannot be explained by an increasing use of support by automation technology.

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 for road transportation. That means that individual and public road transport are responsible for the major share of mechanical drive consumption in Germany.

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 more vehicles are sold which drives 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 [26]. 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 [9].

4.4. The Ratio of Total Factor Productivity and Aggregate Efficiency

Following the approach shown in the MEET2030 project, the ratio of total factor productivity and aggregate efficiency is considered to determine a historical trend. 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 1 in the trend lines only for the time after the reunification of Germany. The considered time series from 1970 to 2014 are presented in figure 1.

However, according to the curves and the ratio of total factor productivity and aggregate efficiency in figure 1 the constant ratio applies for the years from 1991 onwards.

The curves of total factor productivity and aggregate efficiency follow a similar trend, that is shown by the ratio of the two variables. For the scenarios in the next step, the average ratio obtained by the time series from 1991 to 2014 are considered.

5. Scenarios for Germany

5.1. Scenarios for the Individual Road Transportation Sector

The transportation sector has a high potential to increase its second law efficiency which is below average within the economy. Combined with the existing targets from Germany's government for the individual road transportation sector, this sector is taken as the reason to consider this sector in the future scenarios. The focus within the individual road 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.

Electric vehicles have a higher second law efficiency than diesel and gasoline vehicles. 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. 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 fol-

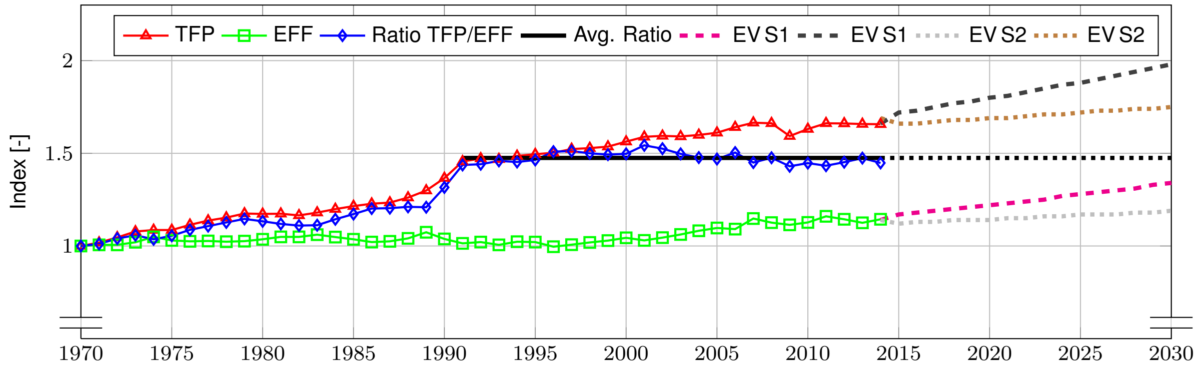

Figure 1: Scenarios of Aggregate Efficiency Index and Total Factor Productivity Index Trend

lowed up to 2030. The second law efficiency of the sectors is assumed to follow the trend from the historical data. The trends for useful work and final exergy are presented in figure 2.

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 1.

Using the resulting total factor productivity to apply the Cobb-Douglas function gives the result in economic output. 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. The indexed values for the economic output and the contribution of capital and labour are presented for both scenarios. 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. The scenarios considering only the contribution of capital and labour as factors of production, show a similar trend for the years up to 2030. 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 development of the electricity generation sector is considered to model the change that is driven by the energy transition. 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 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. 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.

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 individual road 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 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.

6. Conclusion

In the process of finding a solution how to deal with climate change and environmental issues, the focus is increasingly on environmental compatibility that is mainly driven by technological change. The energy sector plays a significant role in the transition process. However, the technological change has a high impact on the economy. Therefore, eco-

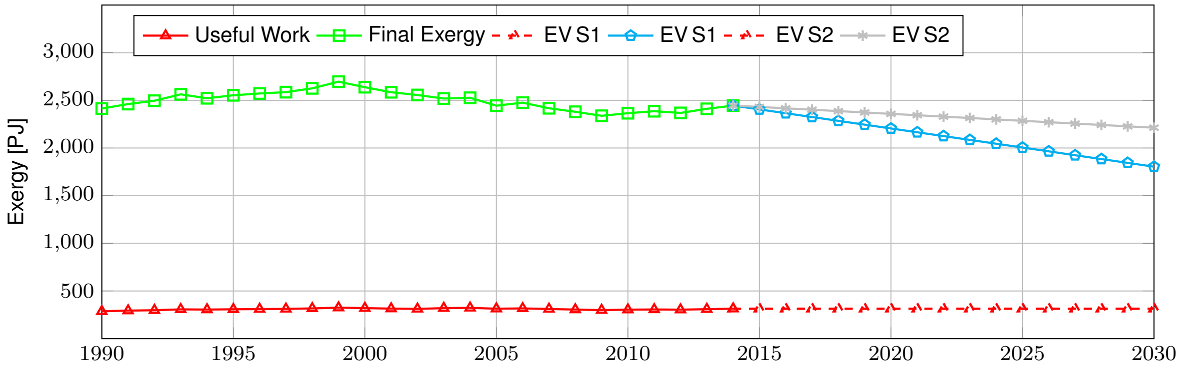

Figure 2: Scenarios for Useful Work and Final Exergy Consumption in the Transportation Sector

nomic analysis is needed to evaluate the development. Economic models are necessary to understand the link between the change in technology and economic growth. The neoclassical economic growth models fail to describe the technological progress as they include it as an exogenous driver for economic growth. Hence, the technological progress needs to be endogenised.

The exergy economic model has been used in this work to examine the link between energy demand and economic growth in Germany. This model allowed the comparison of different technologies regarding their efficiency at the same time. A measure was necessary for a meaningful conclusion about the efficiency of the use of available energy. In contrast to the measure of energy, the exergy approach allowed an estimation of which amount of work is necessary to obtain the desired energy service and to which extend the available energy is used. It has been shown that in Germany the aggregate efficiency that describes the overall thermodynamic efficiency of an economy is linked to the total factor productivity which contributes to economic output and economic growth.

The scenarios presented in section 5 showed that the economic growth will go along with the increase in aggregate efficiency of the economy.

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.

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.

This thesis has presented a model of the German economy that includes energy. 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. 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 next step can be to apply the described model for a specific policy that is developed and check the behaviour of the economy when the policy is applied.

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