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*Research Article*

# Transitioning Towards a Sustainable Energy System: A Case Study of Baden-Württemberg

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**Abstract**

The development and use of renewable energy sources are important to combat current climate change. The paper examines possible pathways to a climate-neutral Baden-Württemberg by 2045, with a focus on a significant reduction in $CO_2$ emissions in the different sectors. In this paper, a reference energy system of the region was modelled using the EnergyPLAN model based on data from 2020. Regarding the expansion targets for renewable energies in Baden-Württemberg by 2040, four scenarios were developed. These focus on the main sectors: transport, heat, industry and electricity. This includes a complete substitution of fossil fuels with renewable energies, and in the industrial sectors, conventional energy is replaced by green hydrogen. In all scenarios, significant $CO_2$ emission reductions of up to 8.68 Mt can be achieved, which underlines the feasibility of climate neutrality in Baden-Württemberg through the expansion of renewable energies and technological change. This work provides some of the key insights needed to further support policymakers and researchers in their work to improve energy systems. This can therefore help to develop better strategies to effectively reduce emissions and thus advance Baden-Württemberg's goals of climate-neutral economy. As this paper was a first step, further research in this direction is needed to successfully achieve these goals.

**Keywords**: Energy System Analysis; Baden-Württemberg; EnergyPLAN; Energy Transition; Renewable Energies; Hydrogen; Electric Car; Industry; Heat Pump; Climate Targets 2030

## INTRODUCTION

With the whole spectrum of environmental challenges increasing and a growing concern about the impacts of climate change, this is an era when the urgency for transition towards renewable and sustainable energy sources has reached an all-time high. This is the reason why the commitment of the world at large to limiting "the temperature increase to 1.5°C above pre-industrial levels", as set forth by the Paris Agreement in 2015 [1] by 196 countries, became rather pivotal.

This goal, however, will require deep changes of the energy systems of countries to decrease greenhouse gas emissions to a large degree and improve structures of energy with a full reliance on renewable energy sources. Among the few nations that have embarked on legally embedding a climate-neutral vision in their national plans, Germany is targeting this goal by the year 2050. The country aims to become greenhouse gas emission neutral in 2045 and has reduction targets for individual sectors until the year 2030 [2]. The government of Germany has different strategies to reach these goals, for example introducing the $CO_2$ tax or expanding renewable energy projects. [3] More and more municipalities are striving to exploit renewable decentralised energy generation. Thereby they participate in municipal projects like "Bioenergy villages" and "100%-Renewable-Energy-Communities" [4]. But is it going fast enough?

More recently, a range of studies highlighted that much improvement was indeed being made, but at such a slow pace to facilitate a proper energy transition process. The EIU forecast that "the transition to renewable energy, though already necessary, will be slow in the coming decade." As much as the power sector is going to be less dependent on fossil fuels, economies will have to pursue decarbonization beyond the electricity generation sector, such as in industries and transport, which are substantial emitters. [5]. It is very important that the focus falls upon these industries and transport because they are among the largest-emitting ones in Baden-Württemberg. The question of how to transition such sectors into cleaner technologies and practices poses one of the main challenges of energy transition [6]. It is a slow transition that relates to the sluggish political changes coupled with the influence that was willed by the energy crisis between Russia and Ukraine. With high inflation, the economic growth witnessed in Germany is pretty slow and hence responsible for less investment in renewable energies. There is also concern about the lack of qualified labour [7]. The integration of renewable energies into an energy system is still in its developmental stage, with a lot of opportunities yet to be tapped.

One of the urgent questions in the expansion of renewable energy sources by Germany is the land competition issue for land use in rural and urban areas. While the "pressure on land" increases, the projects of renewable energy must use space optimally while achieving yields from a renewable source at lowest possible area-based cost. [8] It has, however, been forcibly pointed out in several studies that there is indeed enough space in Germany to cover all its needs from the expansion of renewable energies alone. It is the case of the slow development of wind energy, mainly for reaching renewable energy goals, though it's not unable to be suitably fitted with technology because various planning problems have joined together with the situation of the location of wind turbines [9]. The above barriers underpin a deeper issue of governance, one in which the process for local decision-making is against national objectives.

Whereas climate change is recognized as a global problem that needs internationally coordinated solutions, in actual practice the specific project by project implementation of renewable energy facilities is often a matter left in the hands of local and regional authorities who may lack the funds or the political will to advance such projects [8]. Regarding the expansion of renewable energies, local activities that profit from the exploitation of natural resources, such as land use for agriculture or urban development, usually do not consider environmental costs. In this case, this gap constitutes the necessity of control mechanisms over such activities, making sure that national and international climate goals are met [10]. Without proper accountability in place, local governments may well continue to favour short-term local gains over the diffuse and often longer-term decarbonization benefits accruing globally.

The transition into renewable energy systems is also not only a national issue but also local. [11] With this, many municipalities in the Federal Republic of Germany, among which are those located in Baden-Württemberg, have studied analyses of their respective energy systems to develop climate protection plans. While this is happening, the parallel decentralization of energy production and the varying potentials for renewable energies in the different regions further complicate the transition to Germany's new mix of energy. [9] However, many smaller municipalities do not possess the financial resources and technical expertise that can deal with an assessment of their renewable energy potential or with the effective implementation of such plans [12]. This constitutes a critical barrier that must be addressed if local governments are fully to participate in the energy transition. Fortunately, the energy transition is given new impetus by innovative technologies and changes in consumer behaviour, enabling regions such as Baden-Württemberg to ramp up the pace towards renewable energies [11].

With the growth of renewable energies, energy storage capacities are and will be increasingly needed in parallel [13]. This is particularly true for countries like Baden-Württemberg, because the goal of integrating more fluctuating renewable sources of energy-especially wind and solar power-means a great reliance upon reliable storage solutions. Effective grid operation and energy management have gained much attention worldwide, as renewable energies need to be integrated into energy systems without overloading grids at times of high supply [14]. In Germany, the expansion of renewable energies has taken place in most cases in a decentralized manner, with private individuals and citizen-energy cooperatives increasingly developing renewable energy projects [15].

This report discusses the transition of Germany's prevailing energy system to one that is more dependent on renewables. Given the regional disparities in energy potentials and demands, analysis has been focused on Baden-Württemberg; its current state has been modelled, and four scenarios regarding sectoral changes have been pursued, especially in industry and transport. The reason why the region has been selected is that it represents a very special case within Germany; besides the renewable potential, the sectoral demands and infrastructure challenges differ significantly from the national average. The scenarios therefore simulate various futures and show which pathways are most feasible; going hand in hand is technical feasibility and economic impact [16] For this purpose, a technical analysis with a simulation tool EnergyPLAN will be carried out [17]. The data is based on publications by the Baden-Württemberg State Statistical Office, the Baden-Württemberg Renewable Energy Platform and the Federal Ministry for the Environment, Climate Protection and the Energy Sector [18-20]. In addition, a growing number of energy system models are used whose input values are based on public data [4, 21]. The aim for each scenario is to reduce $CO_2$-emissions, increasing the share of renewable energies, and decreasing overall energy consumption in Baden-Württemberg.

## METHODOLOGY AND MODELLING

This section aims to provide basic information about the EnergyPLAN tool [17], the individual scenarios and assumptions. First, general information about the EnergyPLAN processing tool is given, followed by assumptions that are important for the subsequent process. A brief outlook on data acquisition is also given. Lastly, the method used will be presented.

EnergyPLAN [17] is an hourly simulation model used to simulate energy supply systems. The tool is mainly utilised within energy policy as an analysis tool and serves as a basis for the assessment of energy and technical impacts on energy supply. EnergyPLAN allows for the derivation of energy planning strategies founded on technical and financial analyses, while its output also serves as a sound basis for decision makers within energy planning. The analysis covers, besides the energy and technical effects on the region/nation in question, also the economic and ecological effects. It allows choosing either a technical or a market simulation; the former is more precise, which may lead to better accuracy in simulating systems with a high proportion of intermittent renewable energy. As shown from the flow chart in Figure 1, the program considers all energy system sectors: electricity, heat, industry, cooling, and transport. On the left, in the screenshot, you see headings of the main categories, under which you can insert all the relevant data. The general basic inputs include demands such as heat and electricity, various available energy sources, their capacities, and their costs and regulation strategies. In this respect, the program user may, for example, choose between different regulations: balancing the heat and electricity demand in the region or nation. Through a variety of options offered by the program, it is possible to easily compare different options [22].

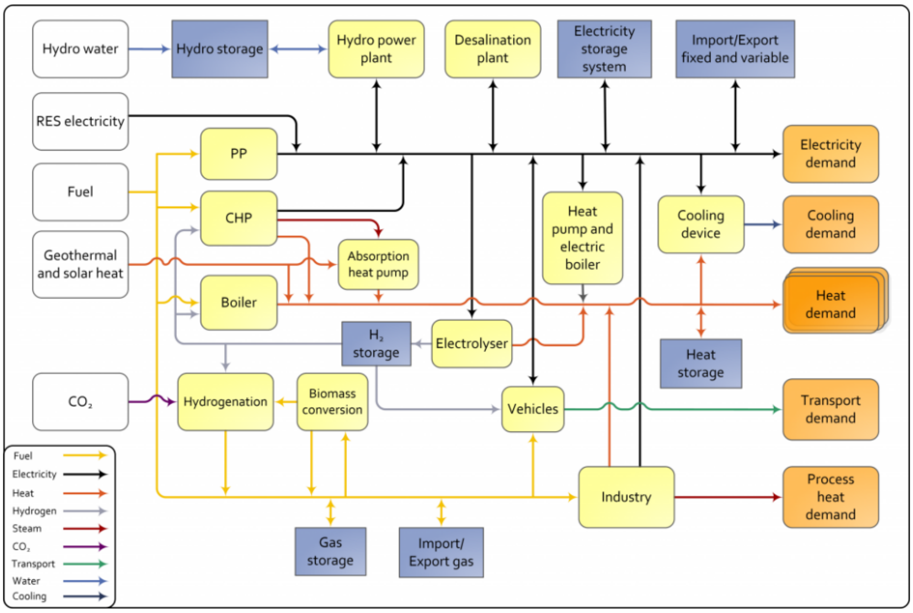



**Figure 1.** Screenshot technology and flow model through EnergyPLAN [17]

## ASSUMPTIONS AND DATA COLLECTION

The collection of data and the decisions made in the course of collection are explained in detail in the following section. The technical analysis of the energy system is based on the creation of a so-called reference model in advance, which represents the current status of the energy system of Baden-Württemberg. In order to get a model result as close as possible to reality, a lot of input data is needed. As mentioned earlier, the modelling tool EnergyPLAN is used to simulate the current system and the different scenarios [17]. The reference year is 2020. This is because it is the latest year for which most of the data was published. Nevertheless, it should be underlined that this is the year of the pandemic, which is why energy production and consumption data is different. As the exact deviations of how the data is offset due to the pandemic is not the focus of this report, further discussion will not be made. Data used in this report are obtained through contacted local authorities, articles, and detailed energy reports from Baden-Württemberg. Most information was found in the energy report from the ministry of environment, climate and energy industry of Baden-Württemberg [18]. This article contained most of the required information on energy demand and energy distribution in Baden-Württemberg. Other important sources were the reports "Baden-Württemberg Klimaneutral 2040: Erforderlicher Ausbau der erneuerbaren Energien" [19] and "Erneuerbare Energien in Baden-Württemberg 2020" [20]. However, some information and data were further processed to be use in the modelling work. Some of the important assumptions and calculations are listed below.

- Heat demand per building: For four areas the heat demand per building was found: For this purpose, Baden-Württemberg was divided into four parts and the mean value for each part was given. The mean value of the four areas was then calculated in order to get the heat demand per building of whole Baden-Württemberg.
- Combined heat and power: the total electric capacities for the CHP stations are calculated and categorised in two groups, plants with a power output of more than 10 MW and plants with a capacity of higher than 100 MW [23].
- CHP efficiency: The efficiencies for the CHP plants are also calculated from various data sources.
- Costs: The data for all the costs of the energy system are provided by EnergyPLAN itself, assuming that the real costs of operating and building the components of the energy system differ not much from the EnergyPLAN data.

## REFERENCE SYSTEM

The reference system, which is defined as a region, is the state Baden-Württemberg, which is located in the south-west of Germany. Baden-Württemberg had 11,102,000 [18] inhabitants in 2020 and cover 35,751 square kilometres [24]. A map of the reference system can be found in Figure 2.

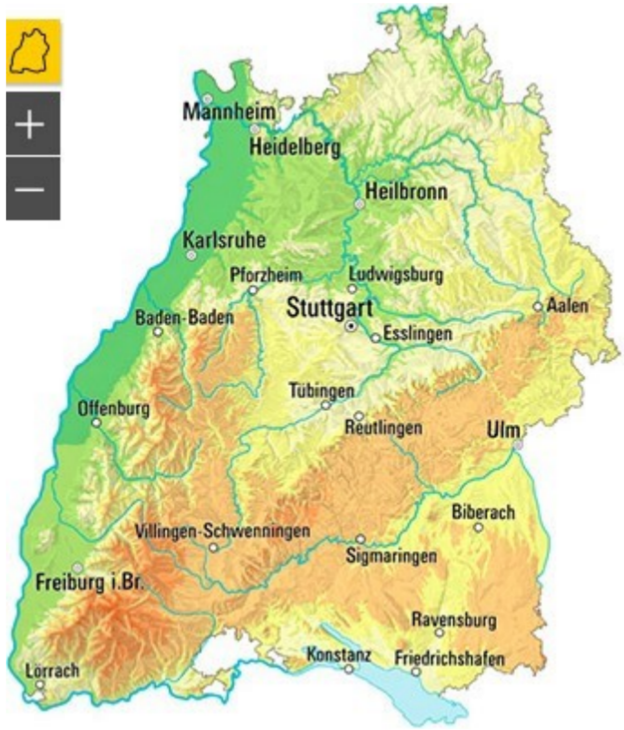



**Figure 2**. Map of Baden-Württemberg [25]

As it can be observed, the area of the reference system is very big and, for this reason, varies in landscape and topography. Based on the topographic map, the altitude within the area ranges from 85 meters above sea level to 1,493 meters above sea level, thereby resulting in major differences with regard to climate and weather conditions. This would mean, in the context of the energy system, far-reaching differences not only in energy demand and energy consumption but also in the different potentials for exploiting renewable sources of energy.

## DEMOGRAPHICS IN THE REFERENCE REGION

As mentioned before, Baden-Württemberg had a population of 11,102,000 inhabitants in 2020, so the average population density is 311 inhabitants per square kilometre [26]. The population living in cities are 2,069,319 inhabitants, so approximately 18,64% [27]. Of the total 35,748 $km^2$, 1,573 $km^2$ are residential areas [26]. An overview of the population data can be found in Table 1.

**Table 1.** Population numbers [26]

| Total Population | Population density per km² | Population in urban areas in [%] |
|---|---|---|
| 11,124,624 | 311 | 18.64 |

As shown in Table 2, the reference system in total contains a number of apartment buildings, detached and semi-detached houses.

**Table 2.** Flats in apartment buildings and detached and semi-detached houses [26]

| Apartment buildings | Detached and semi-detached houses |
|---|---|
| 2.6 million | 2.5 million |

Of the approximately 5.1 million flats, half of them is in detached and semi-detached houses and the other half in apartment blocks. In detached and semi-detached houses, there are 1.3 flats on average, whereas in apartment blocks there are 5.8 flats on average [26].

## ENERGY DEMAND

The next section deals with the energy needs of Baden-Württemberg, differentiated into electrical power and heat. Subsequently, in this article, energy demand for the industry and transportation sectors will be discussed in more detail.

### *Energy demand - Electricity*

The electricity demand of Baden-Württemberg in the selected reference year 2020 was 65.8 TWh. Of this demand, 44.4 TWh were produced in Baden-Württemberg and the remaining 21.4 TWh were imported [18]. Which consumer sectors use how much electricity can be seen in Table 3.

**Table 3.** Electricity consumption by consumer sector [18]

| Sector | Electricity consumption [TWh] | Percentage [%] |
|---|---|---|
| Households | 16.8 | 25.5 |
| Mining and Manufacturing Industry | 24.2 | 36.8 |
| Transport | 1.5 | 2.2 |
| Others | 16.2 | 24.7 |
| Conversion and network losses | 7.1 | 10.8 |

### *Energy demand - Heating and cooling*

In order to cover the heat demand, every building in Baden-Württemberg requires 28,183.2 kWh per year [28]. For this value, the following calculation had to be performed: The demand in heat for four regions in Baden-Württemberg was known. Additionally, the number of buildings in those regions is known. Then for each region, the heat demand per building was computed and then an average value is taken out. Currently, most of the households in Baden-Württemberg heat with oil and gas, as can be seen in Figure 3.

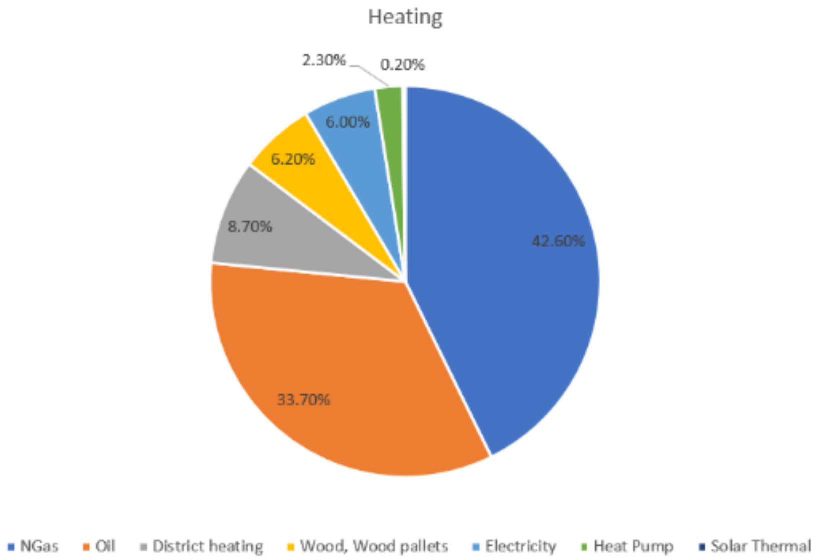



**Figure 3**. Heating type for individual heating [26]

Wood and wood pallets are also widely used for heating, and this was considered in the modelling. In order to reduce $CO_2$-emissions from the building sector, heating systems with 65% renewable energy must be installed in new buildings from the start of 2024 in Germany [29]. For example, the use of heat pumps is to be further expanded, as there are currently just 170,000 installed in Baden-Württemberg [19].

The data used for individual heating are based on the year 2018, but newer data could not be found. However, because a difference of two years would not change anything since heating systems are designed to last long, it has been assumed that shares in percentages have not changed from the reference year 2020. For the boiler efficiencies an article with the topic of boilers was used for efficiency, because no data specific to Baden-Württemberg was found. The average efficiency value for oil boilers is 93% [30] and for gas boilers 94% [30]. District heating plays an important role in Baden-Württemberg, see Figure 4.

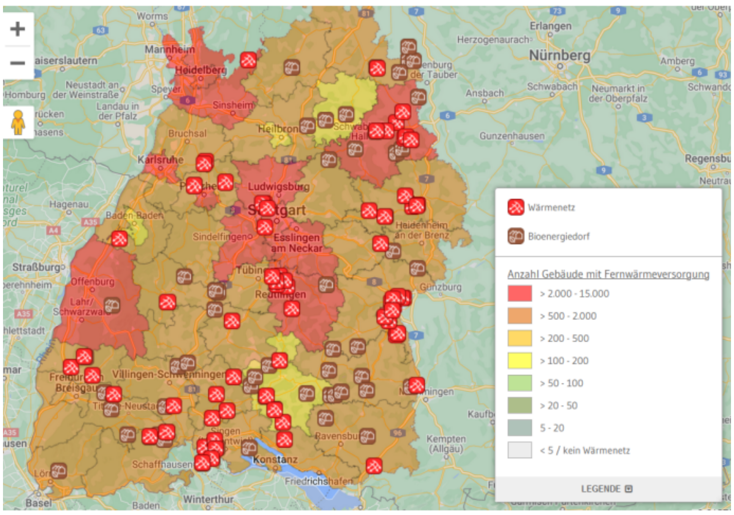



**Figure 4**. District heating map [31]

Although only 8.7% utilise the technology, the district heating network is already well developed. Larger cities, such as Stuttgart, Karlsruhe, Heidelberg and Offenburg, are supplied with district heating, as can be seen in the following map marked in red [31].

As there is no data source in which the heating networks of Germany or Baden-Württemberg are fully recorded, the data from various sources was used and checked for plausibility at the end [32]. To date, district heating has mainly been generated from fossil fuels. 25.9% comes from coal, 41.3% from natural gas, 7.2% from other energy sources such as LPG and heating oil and only 25.5% from renewable energy sources [18]. By contrast, there are only a few cooling networks in Baden-Württemberg compared to the heating networks. In the reference year 2020, there were three cooling networks that had a connected capacity of 39.5 MW. However, because this value is very small when compared to the district heating network, it has been disregarded in the reference system. Nevertheless, the importance of cooling networks could increase in the future, which is why their development should be continuously monitored [33].

### *Energy demand - Industry*

Industry also requires quite a large amount of energy. In 2020, 20% of final energy was consumed by industry. The main industrial consumers of energy in Baden-Württemberg are the paper industry, processing of stones and trades, other industries, and vehicle construction. The exact sources of energy which industry requires are given in Figure 5.

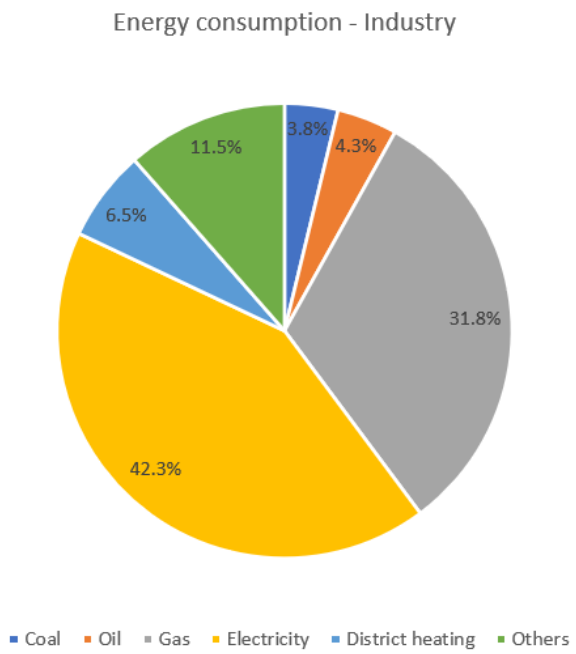



**Figure 5**. Energy consumption of the industry [18]

It is noticeable that the sector primarily requires electricity and gas. The 11.5% share of other energy sources includes sewage gas, landfill gas, solar thermal energy, biomass, hydrogen and heat pumps [18].

### *Energy demand - Transport*

8,236,990 vehicles were registered in Baden-Württemberg in 2020. The fuel consumption has clearly dropped against the recent decade: Diesel by about 15%, petrol by 28% - this with a steep increase in the number of registered vehicles. This value should be put into perspective, since due to the pandemic the need for mobility was comparably much lower in the reference year than in the relevant years. Table 4 shows an overview of the vehicles in the reference system. The majority of vehicles, around 62%, are petrol-powered [18].

**Table 4**. Vehicles of the reference system [18]

| Fuel | Quantity |
|---|---|
| Gasoline | 5,109,529 |
| Diesel | 2,962,923 |
| Electric | 29,461 |
| Others | 135,077 |

About 36% of the cars are using diesel and only 0.4% of the cars are electric. There are also other fuels, which use gas or are hybrid [18].

## ENERGY SUPPLY

The following section looks in detail at the energy supply in Baden-Württemberg, a German federal state. For this purpose, the heat and electricity supply based on available types of power plants and renewable energies will be discussed.

### *Energy demand - Electricity and heating*

Combined heat and power generation is a form of generation whereby the generating plant produces electrical and thermal energy. Electrical energy mainly serves for electricity generation, while thermal energy serves for supplying hot water. This share of combined heat and power generation has been continuously growing in Germany since 2003.Today, combined heat and power generation accounts for around 20% of the electricity and heat supply in Germany [30]. District heating is produced by industry and by power plants in Baden-Württemberg [18]. The plants are divided into two groups: Group 2 comprises all the power plants with installed capacities below 100 MW, while Group 3 comprises all those above 100 MW of installed capacity. In both groups, a distinction between Condensing and Back-pressure is possible. Back-pressure means the pressure developed in case of impediment in flow of fluid. Condensation is a process in which condensed vapour forms back into liquid, applied only for Group 3.The Number of Back-pressure plant on the other hand are composed of 21% of Group 2 power plants and 79% of Group 3 power plants [23].

In addition to the power plants, industry also plays a significant role in heat and power production. The total amount of electricity produced by industry is 3.2 TWh. Industry also produces 9.29 TWh of heat, but at the same time has a demand of 7.74 TWh for it. All three groups in turn are supplied with heat. Group 1 represents district heating systems with no CHP [23]. It should also be noted that 0.107 TWh of district heating comes from geothermal heat [34].

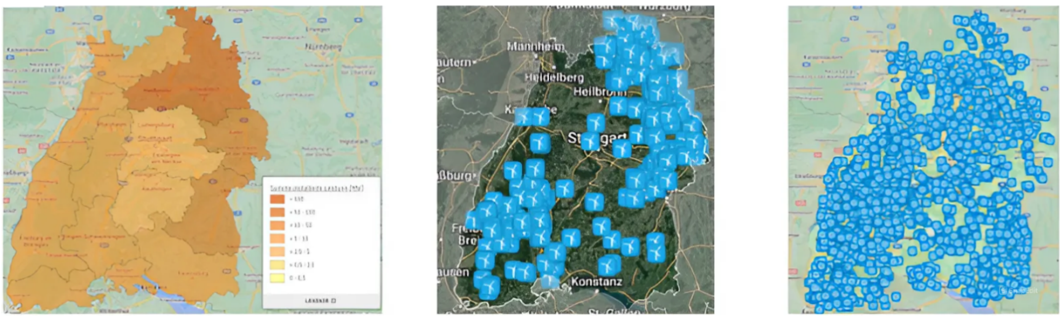
## *Energy supply - Central Power Production*

The Central Power production includes only the generation of electricity and is divided into conventional power plant, nuclear power plants and geothermal power. In total, 3,725.19 MW make up the electrical share of Central Power Production, with 62% being generated by conventional power plants [23] and 38% by nuclear power plants [35], which were still in operation in the reference year 2020 and were only gradually dismantled in 2023 [36]. In the reference year 2020, there was no geothermal power installed [20].

## *Energy supply - Variable Renewable Energy*

In view of Germany's climate targets, renewable energies also make a not insignificant contribution to the provision of electricity. Renewable energies are primarily photovoltaic with a share of 74%, wind power with 15% and river hydro power with approx. 1% [20].

The installed capacity of renewable energies totals 9,370 MW [20]. Also, Biomass accounts for a proportion of the energy supply in Baden-Württemberg and is considered as a fuel for conventional power plant [20]. The installed renewable energies can be seen in Figure 6.




(a) (b) (c)

**Figure 6**. Installed renewable energy in Baden-Württemberg, (a) Photovoltaic [37], (b) Wind power [38], (c) River hydro [39]

## *$CO_2$ – Emission*

As already pointed out in the introduction, Germany, and hence Baden-Württemberg, too is pursuing the objective of reducing emissions. In order to be able to work towards this in the scenarios to come in section *SCENARIOS,* it is important to know the $CO_2$-footprint of the system in advance. Data for Germany was used to enter the $CO_2$-factors for various energy sources in EnergyPLAN [40]. These were then adjusted to the total $CO_2$-emissions of the region, which were known from the energy report [18].

### *Balancing and storage*

Energy storage systems are used to stockpile energy produced but not needed at the specific moment of production yet is available when less energy is available. The section below discusses options available to store electricity and heat.

Since no precise data concerning the given region is at hand with respect to capacity and times of charging/discharging, the estimate calculation would have to be done based on data for all of Germany. The number of installed capacities of home storage systems in Germany is set in relation to the population of Baden-Württemberg. Next, the average charging time can be estimated based on the total output and the capacity of storage systems in Germany. Multiplying the average charging time and the calculated installed capacity of Bade-Württemberg results in a total storage capacity of 271.7 MWh [41]. The same procedure was used to calculate the discharge capacity. The thermal storage corresponds to 3,687 MWh, based on the categorization of the CHP plants and the district heating systems [20]. When it comes to the storage of Liquid and gas fuels, Baden-Württemberg only has two storage facilities with a total volume of 221 Mio. $m^3$. With an average storage of 11 kWh gas per $m^3$, the storage facilities can store a total of around 2,431 GWh [42].

### *Costs*

The simulation tool EnergyPLAN provides a cost database, including investment costs, fuel costs, capital expenditure and amortisation period of the individual instances. Along with one-off costs, operating and maintenance costs are also listed, which are repeated at least once a year over the whole amortisation period. The costs from the EnergyPLAN database are prices from 2018, which are sufficient for the reference year [43].

Besides the investment costs, operating costs and the amortization period of the single technologies employed in the heat and electricity supply chain, fuel prices, fuel taxes, and $CO_2$- taxes play an important role in total cost determination. Fuel and $CO_2$ −taxes are levies imposed by the government and the state on fossil fuels such as gas, oil or coal, but also on renewable energy products such as biodiesel or bioethanol [44]. As the fuels are often not produced domestically and therefore have to be imported, international prices often apply to common fuels, which is why the prices in the reference model correspond to the international prices for 2020 [45].

A list of fuel prices can be found in Table 5.

**Table 5**. Fuel Prices 2020

| Fuel | Prices | Unit | Sources |
|---|---|---|---|
| Diesel | 32.233 | €/GJ | [46] |
| Petrol | 38.65 | €/GJ | [47] |
| Natural gas | 30.85 | €/GJ | [47] |
| Coal | 1.723 | €/GJ | [48] |
| Fuel oil | 7.56 | €/GJ | [47] |
| LGP | 31.0 | €/GJ | [49] |
| Biomass | 8.33 | €/GJ | [50] |
| Nuclear | 1.56 | €/GJ | [51] |

As previously mentioned, mostly every fuel in Germany must be taxed in accordance with the Energy Tax Act [44]. The tax rate differs depending on the type of fuel and the source of consumption. A list of taxes relating to households, industries and boilers can be found in Table 6. As non-renewable waste and biofuels are not taxed, no taxes are payable on the use of CHP [52].

**Table 6**. Fuel Taxes 2020 [52]

| | Individual households | Industry | Boiler at CHP Plants |
|---|---|---|---|
| Coal | 4.0 €/GJ | 4.0 €/GJ | |
| Diesel | 2.0 €/GJ | | |
| Natural gas | 1.8 €/GJ | 1.8 €/GJ | 0.7 €/GJ |

In addition to fuel taxes, there are also taxes on electricity for energy conversion, which are also divided into DH systems and households. The taxes for the respective components can be found in Table 7.

**Table 7**. Taxes on electricity for energy conversion 2020 [53]

| | DH systems | Houses |
|---|---|---|
| Electrical heating | 3.78 €/MWh | 16.7 €/MWh |
| Heat Pumps | 3.78 €/MWh | 16.7 €/MWh |
| Electrolyser | 3.78 €/MWh | 16.7 €/MWh |
| Electric cars | - | 16.7 €/MWh |

Apart from fuel prices and taxes, the $CO_2$- tax has to be paid on top, which should lower greenhouse gases by raising the original prices. For the reference year 2020, the price was just below 28 €/t$CO_2$ [54]. At last, adding the cost data from EnergyPLAN as well as the taxes and fuel prices, the total costs amount to 30,250 Mio.€. It follows Figure 7 in giving the cost breakdown.

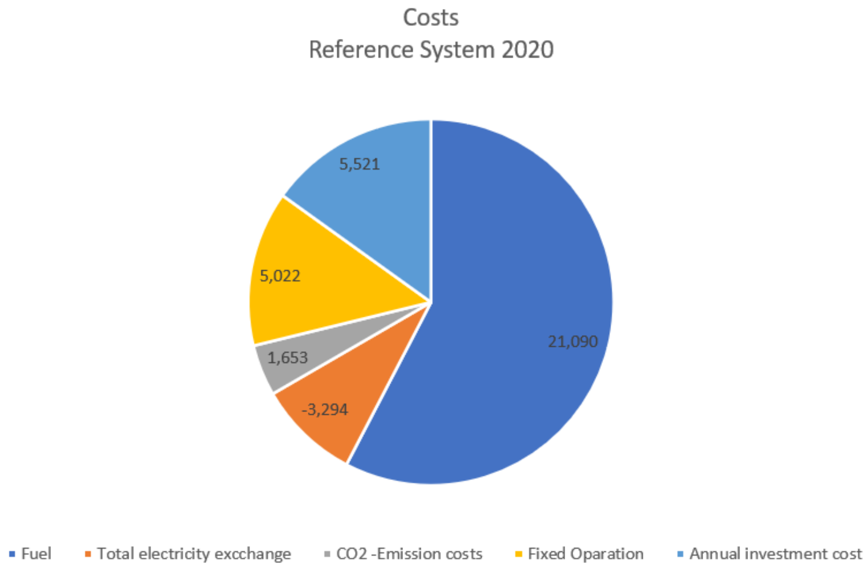



**Figure 7.** Presentation of the composition of total costs

## SCENARIOS

This section highlights various scenarios developed to attain the reduction target of the government for greenhouse gases. All scenarios were designed for the year 2030, as the German and Baden-Württemberg governments have set a number of intermediate targets on the way to complete greenhouse gas neutrality in 2045 [19]. The following four scenarios are designed to reflect reality and hence realisable given the government's targets on climate. Their background in each scenario is given together with the design in Energy PLAN. Nuclear power plants were not changed in the three scenarios 1-3 compared to the reference system. This is despite the fact that they were shut down in 2023 and hence no longer apply in the chosen year 2030. In this case, their usage is for ease of comparison with the reference model. This makes it easier to compare the electricity demand, emissions and costs of the first three scenarios. This changes in Scenario 4, as the focus here is on the supply of energy. Nuclear energy is then reduced to zero and is replaced by the expansion of renewable energy sources [36].

### *Scenario 1 - Electrification of transport through renewable energies*

Germany has set a goal for itself to reduce greenhouse gas emissions by 55% in 2030 compared to the status in 1990. Baden-Württemberg also wants to follow this goal; therefore, it needs to restructure those segments of areas such as transportation. As the transport sector was responsible for 28% of greenhouse gas emissions in the area in 2020, much will have to be changed regarding that. On one hand, the number of vehicles is to be reduced and public transport, cycle paths and footpaths are to be expanded. On the other hand, vehicles are to be increasingly electrified and converted. From 2025, electricity-based fuels such as hydrogen are to be used as a fuel when the direct use of electricity from renewable energy sources reaches its limits or is not practicable, for example in freight transport, shipping or aviation [19]. Special attention was given to the scenarios of car fleet electrification and car fleet reduction. This is evidenced by the scenarios that show one of the ambitions of Baden-Württemberg-to increase the share of electric cars up to 13.2% by 2030. Furthermore, the number of vehicles is expected to fall by 29.6% to a total of 5.8 million [57]. EnergyPLAN distinguishes between two different electrifications of vehicles: smart and dump charging. Since it cannot be known precisely how many of each type there will be in either Germany or Baden-Württemberg, it is assumed that all dump charge cars in the reference system will also be used in the scenario by 2030. All newly added vehicles use smart-charge technology, as this is being increasingly expanded from a lot of companies [58]. On the other hand, electrification is giving rise to electricity demand. This electricity has to come from renewable energies; otherwise, it does not make much sense because one wants to achieve a reduction in emissions through the electrification of vehicles. Owing to the increasing demand, Baden-Württemberg, especially, is expanding its wind and photovoltaics. In this scenario, the focus will be on these two renewable energy sources, since they will play a major role in the region in the future, and that will be more deeply explained in section Scenario 4 - Electricity generation from renewable energies [19].

The following changes are assumed in this scenario:

- Reduce the use of petrol in transportation from 24.4 to 15.0 TWh/year.
- Reduce the use of diesel in transportation from 48.2 to 29.7 TWh/year.
- Change the vehicle charging, which is assumed to be 66% from smart charges and 34% from dumb chargers.
- Expansion of wind energy by 1.50 TWh/year.
- Expansion of photovoltaic by 2.67 TWh/year.

### *Scenario 2 - Increased use of heat pumps and renewable energies*

The households in the region are currently responsible for 29% of emissions [18]. The following measures are foreseen to reduce the heating system's emissions in the region of Baden-Württemberg: First, renewable heat generation based on biomass, solar thermal energy, environmental heat with the help of electricity-powered heat pumps, and geothermal energy should be expanded, see Figure 8. Geothermal energy is a renewable energy resource that can be used to provide electricity, heating, and cooling of commercial and domestic buildings and other facilities [59]. GSHP systems use most commonly electricity and less frequently gas to operate their heat pumps. A typical heat pump has

COP of around 4 [60] indicating that the heat pump produces four units of heating energy for every unit of electrical energy input [61].

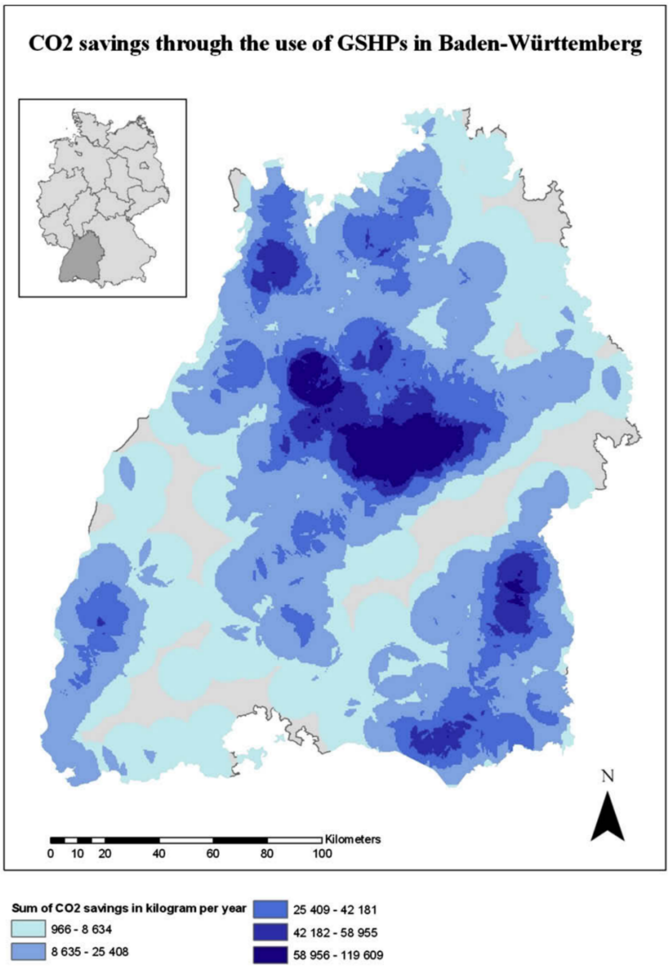



**Figure 8.** Total $CO_2$ savings in kg per year for all installed GSHP systems of the subsidy program using the conservative $CO_2$ savings based on the German electricity mix with 594 g $CO_2$/kWh [62]

On the other hand, heat consumption is to be reduced by 8.3% at the same time [63]. This can be achieved through various measures: insulating the facade and roof, replacing windows, ventilation with heat recovery or the use of an energy management system [64]. As already mentioned in section Energy Demand - Heating and Cooling, a law in Germany for more climate-friendly heating systems will come into force in 2024 [29]. Since this law also is going to increase the use of heat pumps, this scenario focuses on the dispersion of heat pumps in individual households and the reduction of heat demand by potential savings. While around 170,000 heat pumps were installed in Baden-Württemberg in 2020, this figure is set to rise to 500,000 systems by 2030 [19]. This will produce 5.5 TWh/year of environmental heat, which equals a share of 12% of individual heating systems using heat pumps. Heat pumps based on air, geothermal energy, and groundwater will be applied by households. The number of oil and gas heating systems is radically reduced in that scenario. As this scenario only contemplates an increase of heat pumps, but not solar thermal, geothermal, and biomass, the numbers referring to oil and gas heating systems are still relatively high compared to the 2030 forecasts. In addition to increasing heat pumps, this scenario includes an 8.3% reduction in heat demand. In any case, heat pumps raise the demand for electricity here, too, which has to be provided by renewable energies. As in scenario 1, electricity from wind and photovoltaic will be expanded in this scenario [19]. Based on the above points, the scenario is designed as follows:

- Reduce the use of oil boilers in individual heating from 22.77 TWh/year to 19.08 TWh/year.
- Reduce the use of natural gas boilers in individual heating from 26.25 TWh/year to 22.00 TWh/year.
- Increase the use of heat pumps in individual heating from 1.79 TWh/year to 5.5 TWh/year.
- Expansion of wind energy by 1.98 TWh/year.
- Expansion of photovoltaic by 3.52 TWh/year.

### *Scenario 3 - Use of hydrogen in the industrial sector*

It is set against the climate targets of Baden-Württemberg, where hydrogen is to play an important role in security of supply by 2045, amid the current climate crisis and energy crisis. Green hydrogen, which requires the electricity needed to produce hydrogen by means of electrolysis, can make a major contribution to achieving the climate targets through climate-neutral production and conversion [65]. Hydrogen has an ideal pre-requisite for industrial applications, in particular for the steel, paper, glass, and sugar industries, due to its high process heat up to 400 °C. The implication of this is that the scenario relates to hydrogen utilization in industry only. Already, by the reference system, 3.1 TWh/year of hydrogen are produced for the industry. Hydrogen production in Baden-Württemberg will be more than doubled until 2030. The forecast hydrogen production is therefore 7 TWh/year in 2030 [65]. This is achieved by applying renewable energies, which supply the necessary electricity for the production of hydrogen through electrolysis, allowing hydrogen to be referred to as green hydrogen. The scenario relies exclusively on PV and wind energy, as these two energy producers are expected to see the largest increase in installed capacity [66]. Hydrogen, with its chemical composition and properties, has high demands for the transport and storage technology used. As it is already possible today and there are also some applications for transporting hydrogen in natural gas pipelines or mixing it with natural gas, the proportion of green hydrogen produced is deducted from the proportion of natural gas in the scenario [67].

The following changes are made in this scenario:

- Increase hydrogen fuel consumption from 3.1 TWh/year to 7 TWh/year.
- Increase the electrolyser capacity from 485 MW to 1093 MW.

- Increase electricity demand by 5.34 TWh/year.
- Expansion of photovoltaic by 6.13 TWh/year.
- Expansion of wind energy by 3.45 TWh/year.
- Decrease Natural gas by 3.9 TWh/year.

### *Scenario 4 - Electricity generation from renewable energies*

The share of the electricity sector in the generation of $CO_2$-emissions in the reference year 2020 is around 15% [18]. The above period similarly saw a decline in the amount of $CO_2$-emissions due to the outbreak of the pandemic in the same year and consequently reduced demand for electricity as workplaces and buildings were closed. However, as emissions rose again slightly in the following years, it is more important to reduce electricity demand and switch to renewable energies in order to achieve climate protection targets [19]. The focus currently set in Baden-Württemberg is first and foremost on increasing wind and solar energy. Expansion plans are also set for hydro power, biomass, and deep geothermal energy. The aim is to cover around 60% of Baden-Württemberg's gross electricity consumption with renewable energies by 2030 [19].

The expansion of renewable energies is planned as follows, see Table 8:

**Table 8.** Development of electricity supply from renewable energies [19]

| Producer [-] | 2020 | | 2030 | |
|---|---|---|---|---|
| | Installed capacity [MW] | Power [TWh/year] | Installed capacity [MW] | Power [TWh/year] |
| Photovoltaic | 6934 | 6.4 | 24170 | 23.13 |
| Wind | 1587 | 3.0 | 6972 | 13.06 |
| Geothermal | 0 | 0 | 60 | 0.3 |
| Hydro Power | 888 | 4.2 | 930 | 4.65 |

While according to Table 8, installed capacity will be more than four-fold for the photovoltaic sector, attaining almost 23.13 TWh / year by 2030, electrical energy from wind power is expected to grow by about 10 TWh / year by 2030. As hydro power in Germany is largely exhausted [68], the increase in installed capacity is slight and amounts to just under 42 MW. On the contrary, deep geothermal energy, up to this point, with no share in electricity generation considered, will have some addition until the year 2030. An installed capacity of 60 MW is planned [19]. In all, the electricity from renewable energies will increase from 13.6 TWh/year in 2020 to 41.14 TWh/year. Scenario 4 focuses on the reduction of the $CO_2$-emissions by substituting the fossil-fuelled electricity generators with renewable energies. The gains of renewable energies shown in Table 8 are deducted proportionate in line with the decline of fossil fuels expected for the coming years. In order to maintain clarity, it was assumed that the demand for electricity remains the same at 65.8 TWh/year [19]. The following scenario also includes the gradual phasing out of nuclear power from 2023 onward. By the year 2030, all nuclear power plants are switched off, and therefore the percentage of generated electricity with the help of nuclear power plants is set to zero.

Consequently, the following changes are made in this scenario:

- Increase wind power to 13.06 TWh/year.
- Increase photovoltaic to 23.13 TWh/year.
- Increase geothermal power to 0.3 TWh/year.
- Increase hydro power to 4.65 TWh/year.

## RESULTS AND DISCUSSION

The following section elaborates on the results of each scenario: first, how the demand for electricity is changing and how it is being met; second, the emissions and costs of the scenarios and their comparison to the reference system; and lastly, how the different scenarios compare among each other.

### *Results of Scenario 1 - Electrification of transport through renewable energies*

As already described in section "Scenario 1 - Electrification of transport through renewable energies," Scenario 1 aims to reduce $CO_2$-emissions from road transport. To this end, the increase in electric cars is considered, which is estimated to be just under 765,600 in 2030 [19]. This is because, with the rise in electric cars, there is a greater demand for the consumption of electricity. In Figure 9, it has been seen the increase in demand for electricity due to the need for charging the vehicles with the use of electricity increases by just about 5%, to about 68.75 TWh/year.

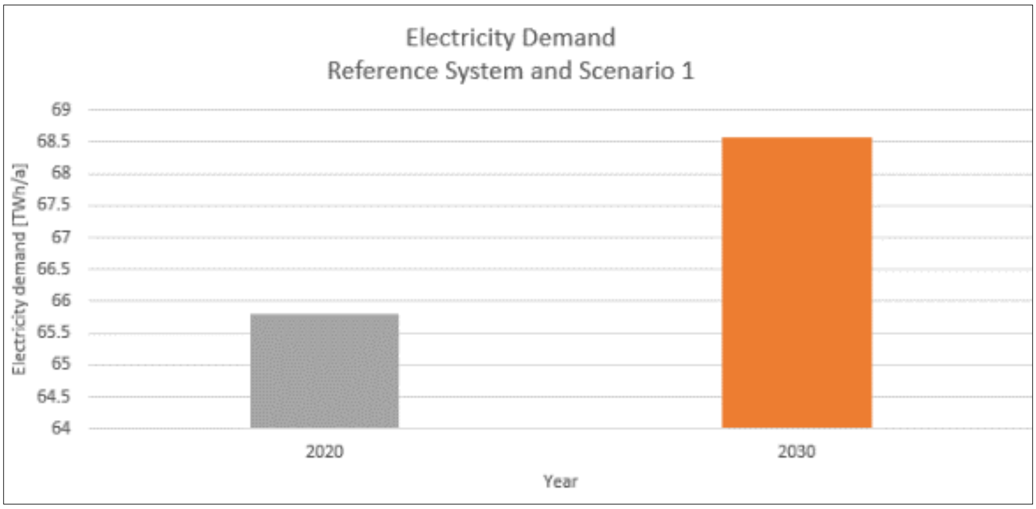



**Figure 9**. Electricity Demand - Reference System and Scenario 1

Renewable energies will have to be harnessed in any case for the emissions to go down since demand goes on an upward trend. Wind and solar energy are the main focuses, as has already been mentioned. This would mean that with increased demand for electricity transport, 9,699 MW for photovoltaics and 2,632 MW for wind farms should be installed. The distribution and the increase in electricity generation of the individual producers are shown in Figure 10.

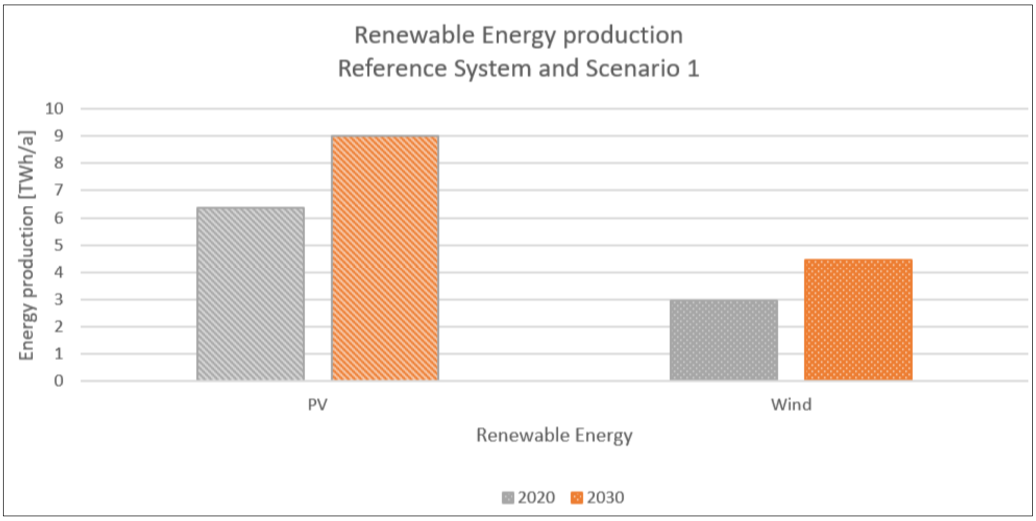



**Figure 10.** Renewable energy production - Reference System and Scenario 1

Besides increasing the share of electric cars, this scenario also considers a general decrease in the number of vehicles. This is due to forecasts from the climate protection scenario concerning Baden-Württemberg transport infrastructure up until 2030.As already described in detail, the number of vehicles is expected to fall by 36%, with the share of electric vehicles accounting for 13% [57]. With these projections, it will be possible to define what the fuel needs are for the year 2030. It is seen from Figure 11, as would be expected, that the demand for fossil fuels, such as diesel and petrol fuels, is going down, while that for electricity will see a minimal rise.

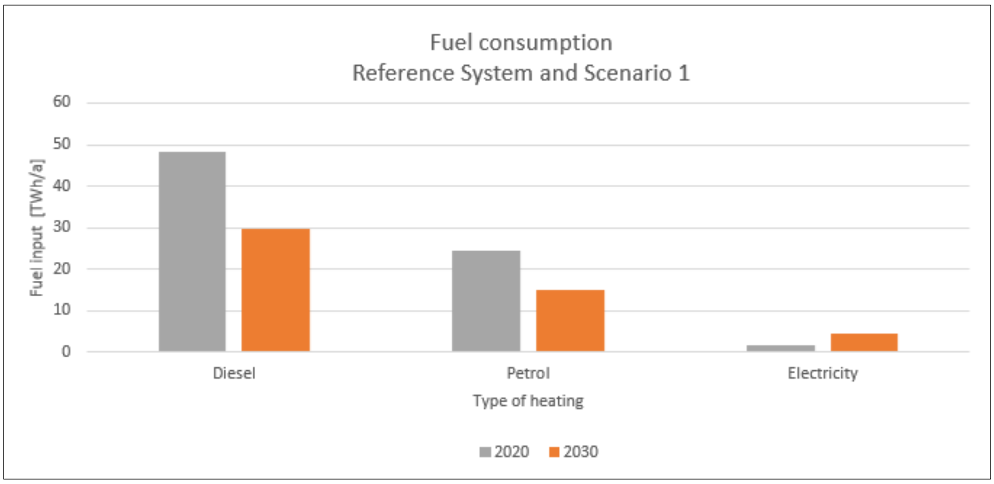



**Figure 11**. Fuel consumption - Reference System and Scenario 1

The decline of the fossil fuel is reflected in the $CO_2$ too: these have fallen by 15% to just under 50.64 Mio. $tCO_2$ per year, as seen in Figure 12. due to the expansion of renewable energies and reduction in fossil fuels. The difference in the emissions clearly comes forward and is an important step toward climate neutrality. In order to achieve these goals, however, the transport sector also needs measures apart from transport electrification-like hydrogen and biofuels.

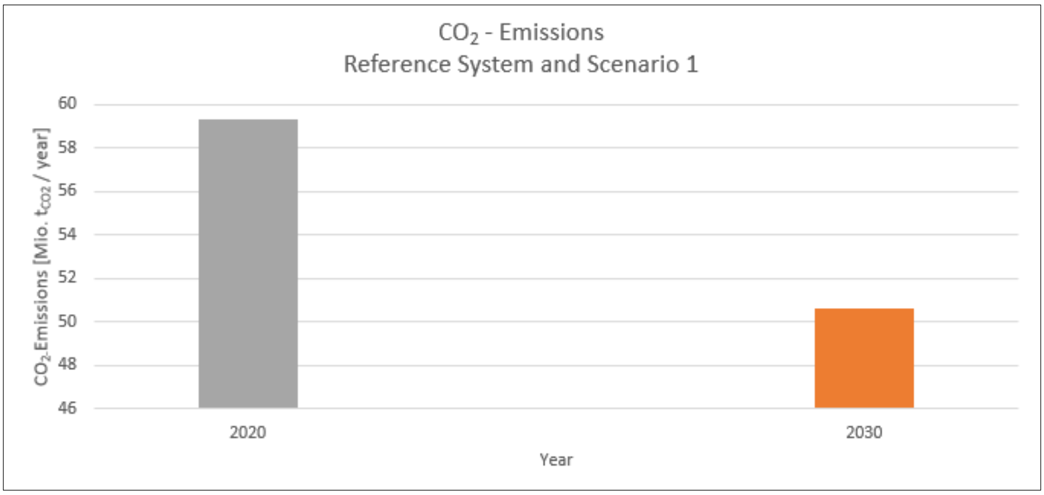



**Figure 12**. $CO_2$-emissions - Reference System and Scenario 1

The use of renewable energies-powered electric cars will also favourably affect the costs. By substituting the fossil fuels diesel and petrol, fuel costs and $CO_2$ costs will decrease considerably. Only the fixed operation and annual investment costs will increase because of the of the new technologies and the resulting maintenance and operating costs. Figure 13 below shows the correct cost comparison between 2020 and 2030.

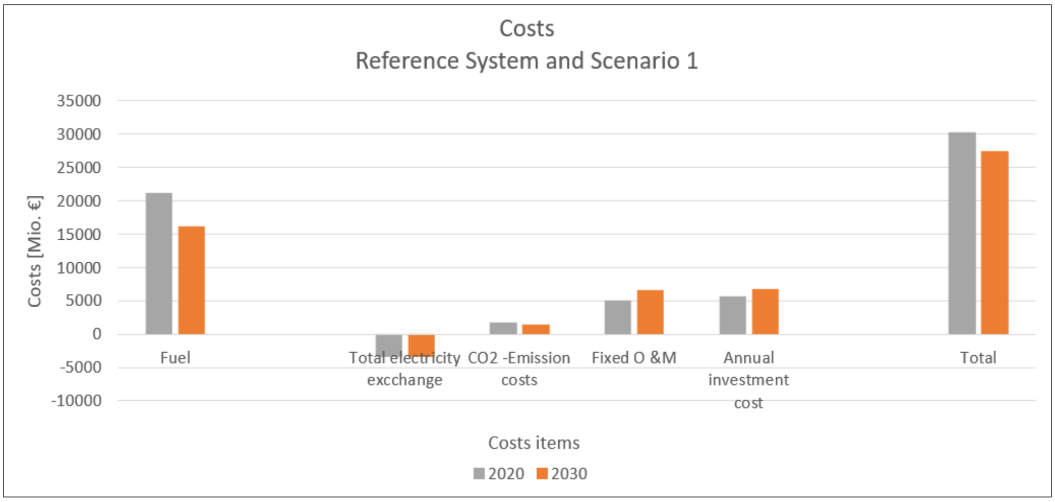



**Figure 13.** Costs - Reference System and Scenario 1

### *Results of Scenario 2 - Increased use of heat pumps and renewable energies*

This scenario, as pointed out in section "Scenario 2 – Increased use of heat pumps and renewable energies," focuses on upgrading the individual heating in the system. Here, oil and gas heating systems are progressively replaced by heat pumps. According to the "Bundesverband für erneuerbare Energien", heating demand will fall by 8.3% to 46.58 TWh by 2030 [63]. As illustrated in Figure 14, total electricity demand increases from 65.8 TWh to 66.81 TWh because the increased installation of heat pumps raises electricity consumption by the heat pumps.

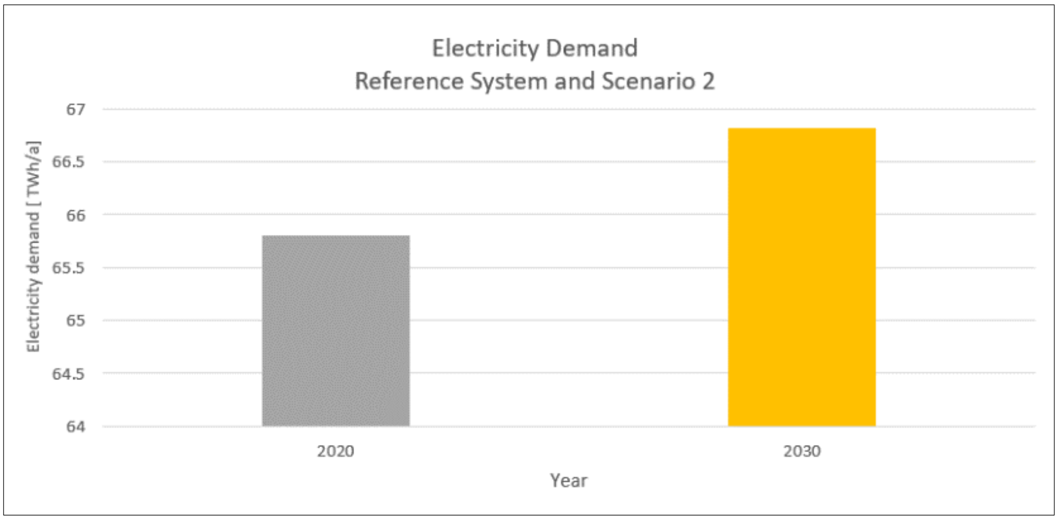



**Figure 14**. Electricity demand - Reference System and Scenario 2

In order to meet this higher demand, wind and photovoltaic are being expanded in the scenario, as can be seen in Figure 15.

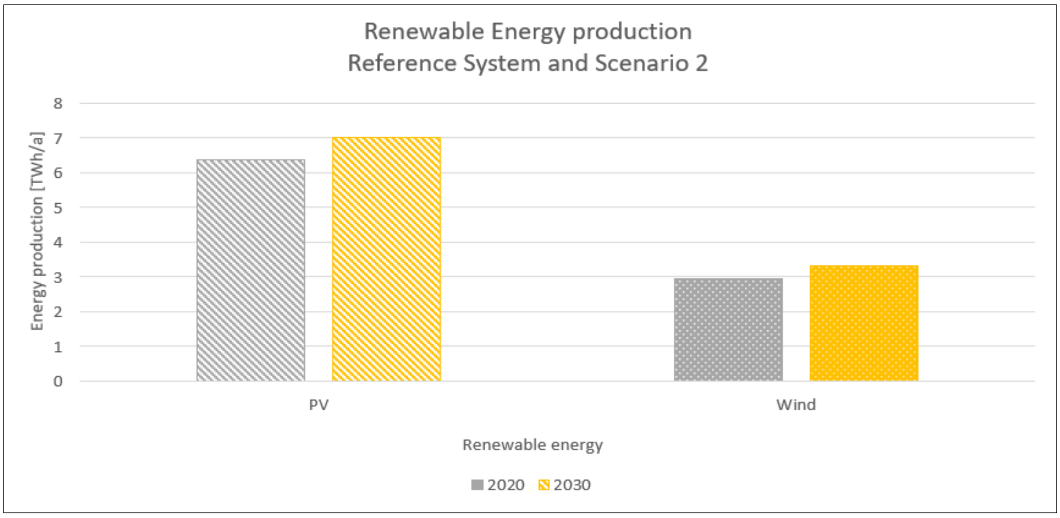



**Figure 15**. Renewable Energy production - Reference System and Scenario 2

Another important thing to be taken into consideration is fuel consumption variation for individual heating. In Figure 16, fuel consumption by gas and oil in that scenario is decreased because some households switch to heat pumps. Biomass is, however, taken up as a renewable source; therefore, its fuel consumption is constant.

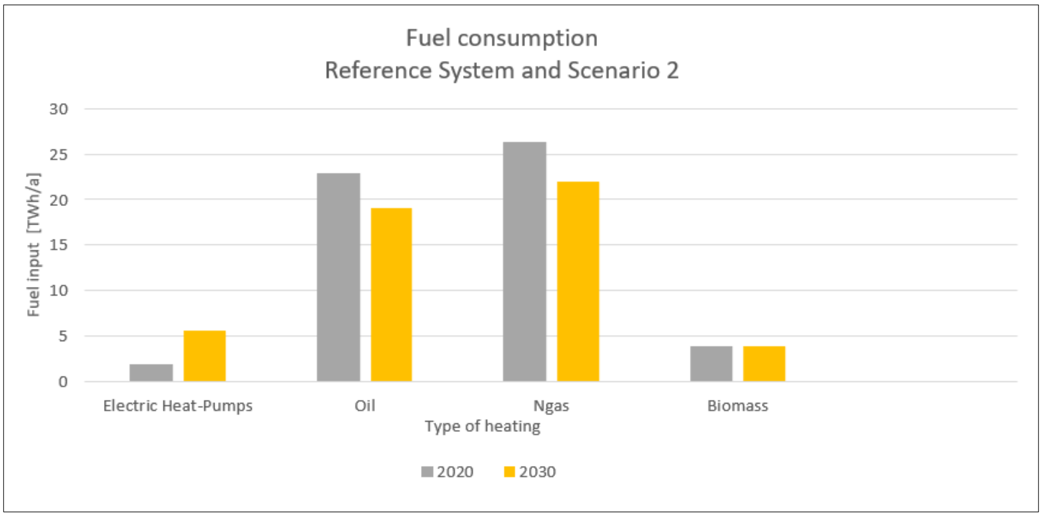



**Figure 16**. Fuel input individual heating - Reference System and Scenario 2

The measures implemented in this scenario have a certain influence on the emissions of the energy system. Due to the reduced number of oil and gas heating systems and the reduced heat demand, $CO_2$-emissions have fallen to 57.65 million tonnes of $CO_2$ per year. This is shown in Figure 17.

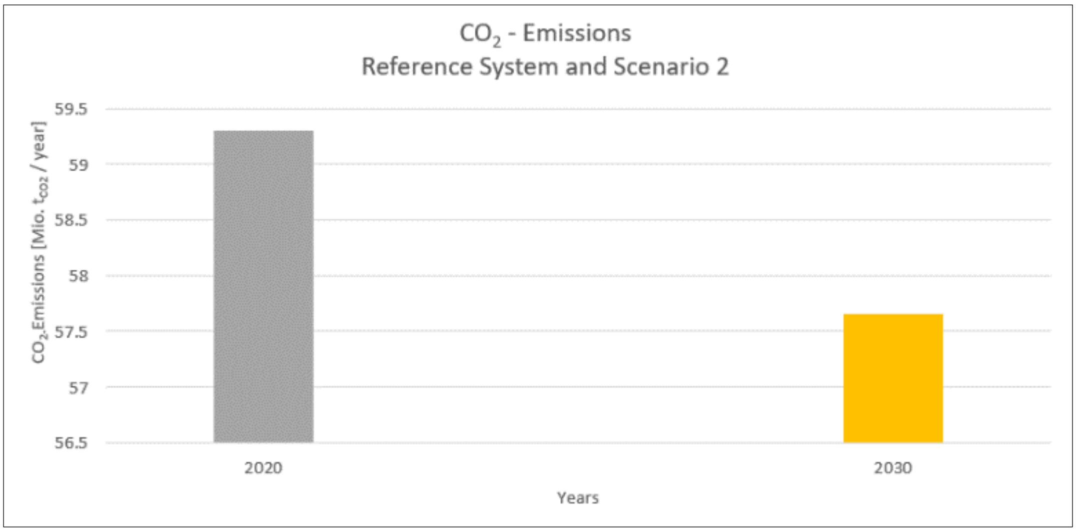



**Figure 17**. $CO_2$-Emissions - Reference System and Scenario 2

This reduction of less than 2 million tons of $CO_2$ will be too little to fulfil Baden-Württemberg's climate targets or to achieve further cuts. For this, much more is needed in the private sector. When it comes to heating systems, reaching the target through heat pumps expansion is one thing, but other renewable heat sources such as solar thermal need to be expanded together with it. In this regard, the expansion of heat pumps, as the scenario given above stands, is a good beginning, but it is completely not enough for the substantial reduction of emissions. The costs for scenario 2 are given in Figure 18.

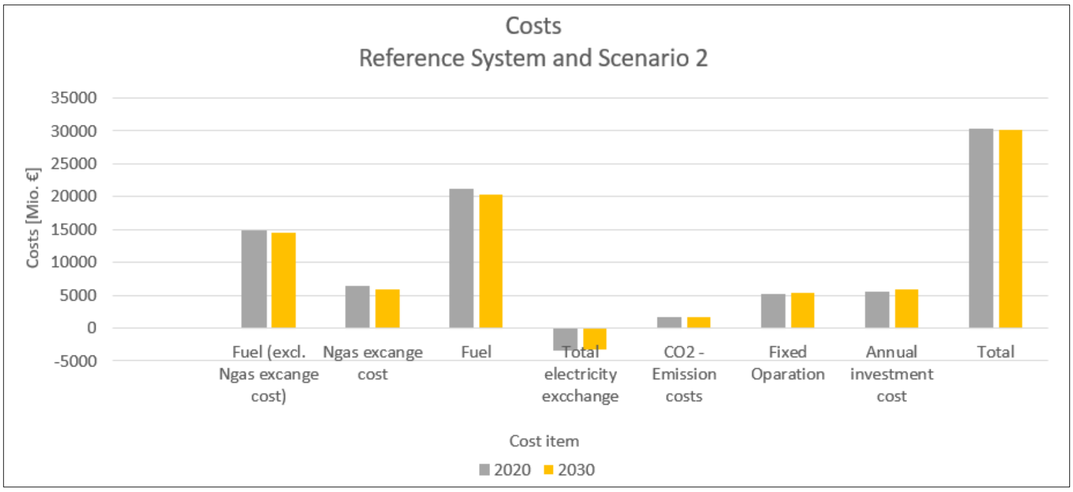



**Figure 18.** Costs - Reference System and Scenario 2

As it can be seen, the costs of the reference system are compared with the costs of the scenario. It can be seen in the figure that the totally annual costs of the scenario are reduced by 65 million € compared to the reference system. Heating savings and reduced consumption of oil and gas is the result of this. The costs are not enormously reduced, because new heat pumps are invested, and wind and solar energy are increased.

The figures for oil and gas heating systems remain high compared to the 2030 forecasts. This is because the scenario considers only the expansion of heat pumps, excluding other renewable heating systems such as solar thermal, geothermal, or biomass. To fully transition the heat market, all types of renewable heating systems must be implemented and considered.

### *Results of Scenario 3 - Conversion of the industrial sector to hydrogen*

As outlined in Section "Scenario 3 – Use of Hydrogen in the Industrial Sector," this scenario focuses on the application of hydrogen in industry. The forecasted hydrogen demand for the industrial sector in 2030 is 7.0 TWh/year. Based on this demand, the required electricity for green hydrogen production will be sourced from renewable energy. The electricity generated from renewable sources, including photovoltaic and wind energy, will offset the demand for natural gas. Given that electrolysers are installed to meet the electricity requirements for the conversion process, the overall electricity demand in this scenario increases by 7%, reaching 71.14 TWh/year, as shown in Figure 19.

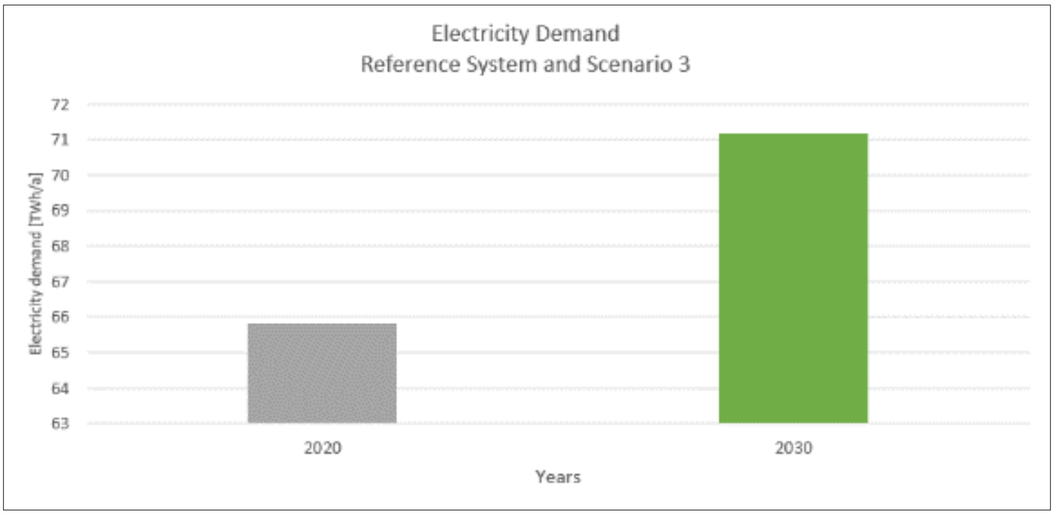



**Figure 19.** Electricity demand - Reference System and Scenario 3

It has been seen previously that hydrogen should be produced from renewable energies. As described, the spread of wind energy and photovoltaics is the main focus in Baden-Württemberg; thus, the scenario is limited to supplying energy from these two sources. In terms of demand, it requires the installed capacity of photovoltaics to be 13,232 MW and wind energy to be 3,389 MW, which corresponds to an increase of just under 150% in each case. Correspondingly, in Figure 20, there is generation of 12.49 TWh/yr from photovoltaics and 6.4TWh/yr from wind energy, representative of the energy that is produced from these sources being twice as much as that produced in 2020.

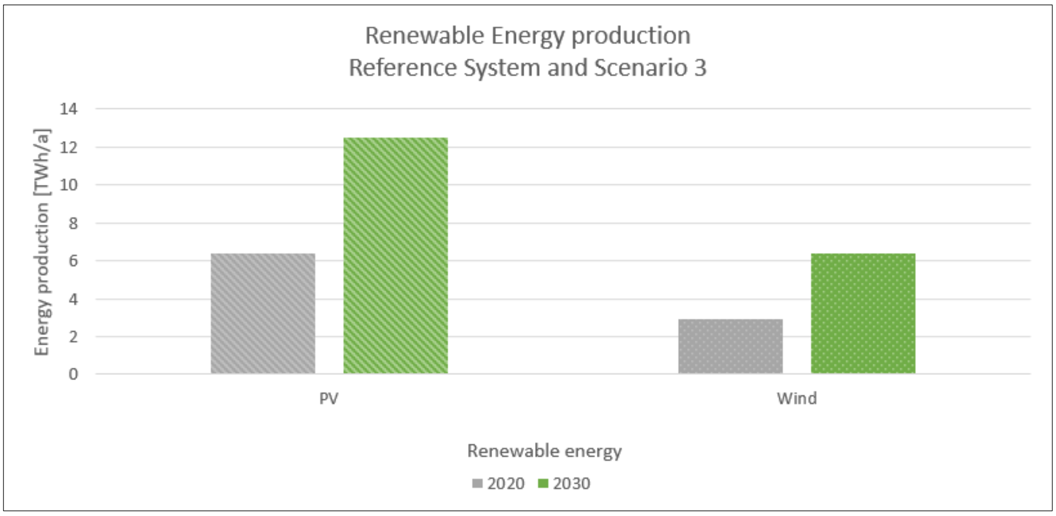



**Figure 20**. Renewable Energy Production - Reference System and Scenario 3

The figures are below the government's planned expansion targets for wind energy and photovoltaic in the region, outlined in Scenario 4 and hence perfectly feasible.

Warning 1 also, in this scenario, was shown at the beginning, which is why the transmission line capacity was increased to 6,410 MW. Again, this is due to the expansion in renewables. Also, the CEEP regulation was set to 7 to reduce the power plants and RES1-4.

Since gaseous hydrogen is very similar to natural gas in its properties and the existing natural gas infrastructure can therefore be used for the transport of hydrogen after converting individual items for hydrogen transport, the hydrogen produced replaces part of the natural gas [67]. The new distribution of fossil fuels is shown in Figure 21 below.

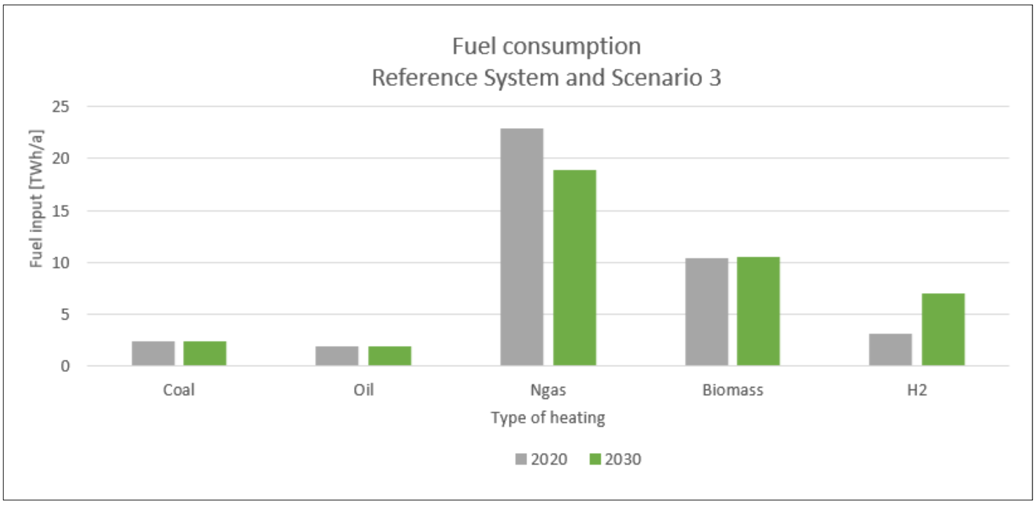



**Figure 21**. Industrial fuel consumption - Reference System and Scenario 3

Due to the reduction in natural gas production, $CO_2$ emissions are lowered, contributing positively to the federal government's climate protection goals. As shown in Figure 22, hydrogen saves 460,000 tonnes of $CO_2$ per year.

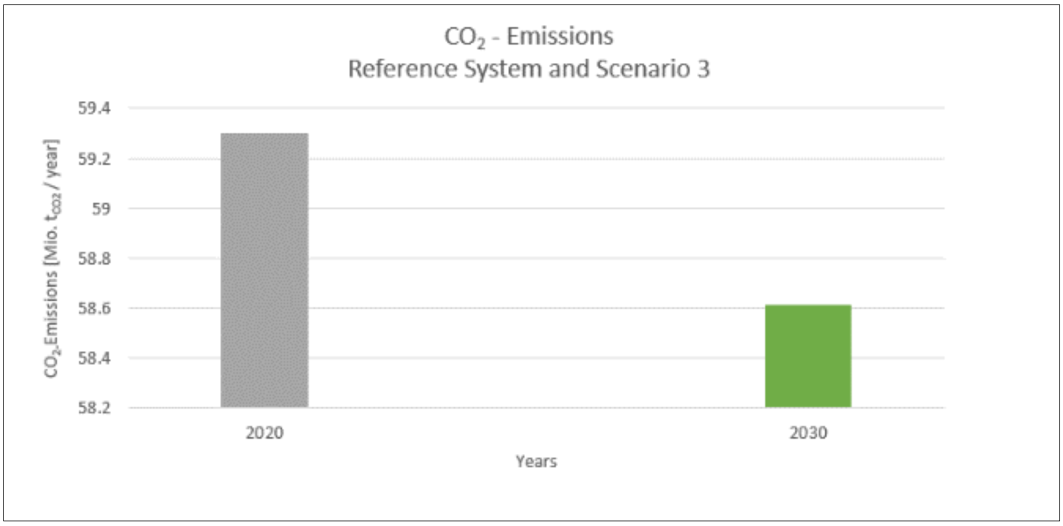



**Figure 22**. $CO_2$-Emissions - Reference System and Scenario 3

Further savings potential can be identified in the expansion of renewable energies, the hydrogen infrastructure, and the gradual restructuring of industry - for example, the steel, glass, paper, and sugar industries. However, hydrogen could play a role in the future not only in industry, but also in the transport sector and in households [67].

Hydrogen applications also have a great impact on the overall cost. As can be seen from Figure. 23, an increase of about 45% is recorded in fixed operating costs and annual investment costs.

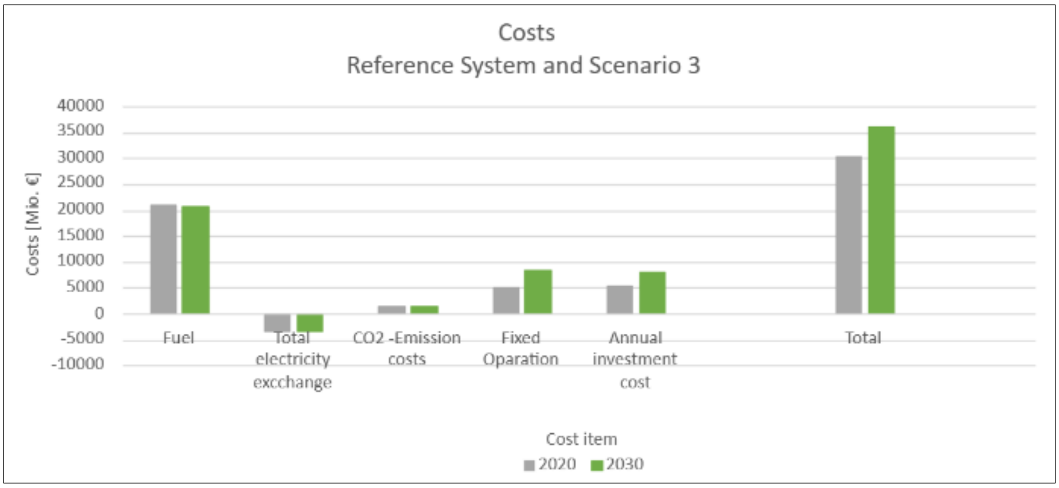



**Figure 23**. Costs - Reference System and Scenario 3

Both cost sectors have increased due to adding the electrolysers and the complex multi-part design of the plant. High demands on the cleanliness and functionality of the electrolyser, which have an immediate influence on the costs, are put in place to keep the efficiency of the plant high and for the purity of hydrogen. This also raises the total costs, which grow from 30,250 Mio. € in the reference year 2020 to 36,146 Mio. € in 2030.

## *Results of Scenario 4 - Electricity generation from renewable energies*

Based on the expansion targets for renewable energies set by Baden-Württemberg, as shown in Table 8 in section "Scenario 4 - Electricity generation from renewable energies," the electricity supply is analysed in more detail in this section. Only in the installed capacity of renewable energies forecast for 2030 is used to cover the electricity demand. Assuming that the demand for electricity will not change in the future, the value remains constant at 65.8 TWh/year. First the power stations with the highest $CO_2$-emissions are shut down and decommissioned and it had to be ensured that nuclear power is switched off. The growth of renewable energies has, therefore, resulted in an overall increase of 27.45 TWh/year compared to the reference year 2020: generation through wind increases 3.5 times, and the electricity generation from photovoltaic systems is fourfold. The contribution to the generation of electricity in 2030 also comes from geothermal and river hydro power, despite the increase being low there. This detailed development may be seen in Figure 24.

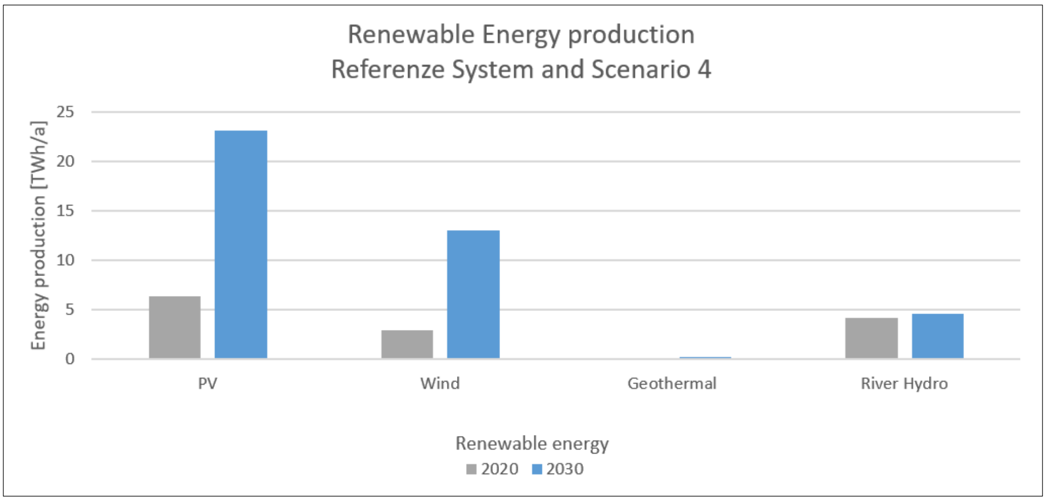



**Figure 24**. Renewable Energy production - Reference System and Scenario 4

The expansion of renewable energies leads to decline in generation from conventional plants, which in turn does have an impact on the quantities of fuel required or used. As can be seen in Figure 25, the fuel quantities of oil, natural gas and biomass are each reduced by approximately 73%.

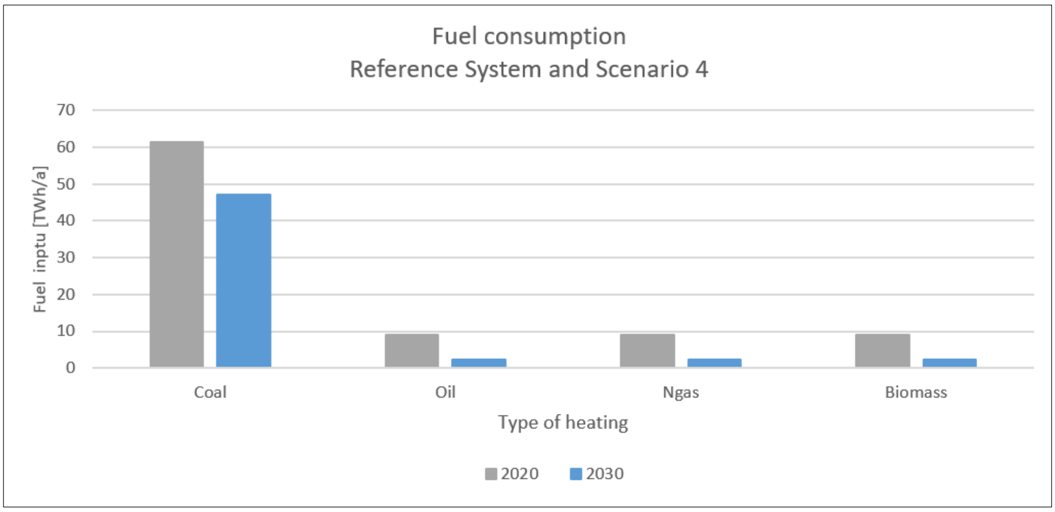



**Figure 25**. Fuel consumption - Reference System and Scenario 4

It also shows a reduction of 23.5% in the use of coal. This in turn also positively influences the amount of $CO_2$-emissions, which can be seen in Figure 26.

Due to the reduced amount of fossil fuels required because of the reduction in use of conventional power plants, less emission is released during electricity production. A decrease on just under 12% to 51.89 $tCO_2$ per year is recorded. However, it must be considered that nuclear energy will also be replaced by renewable energy at the same time. This does not lead to a reduction in emissions, as nuclear energy does not produce huge amounts of $CO_2$ compared to fossil fuel power plants [71].

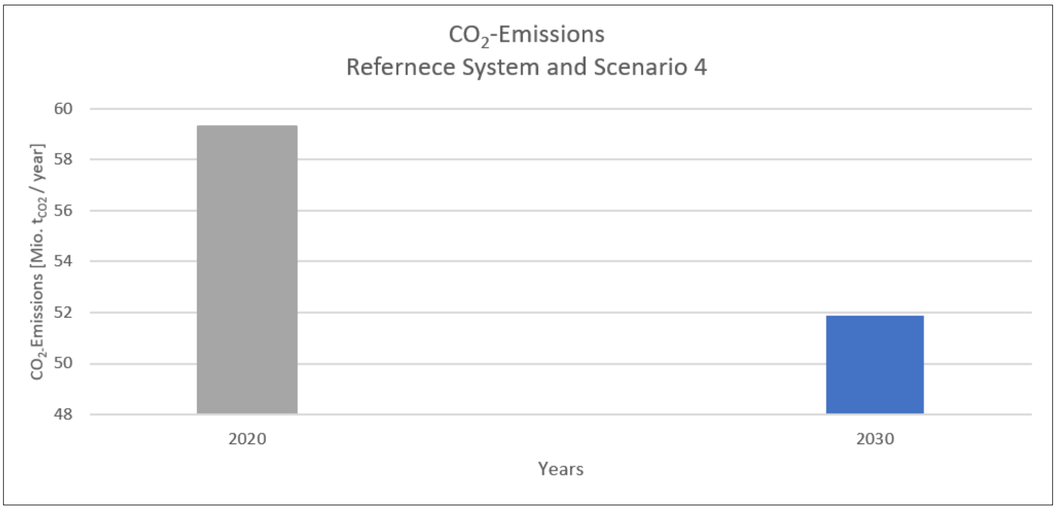



**Figure 26**. $CO_2$ -Emissions - Reference System and Scenario 4

Additionally, changes in the supply of electricity also have an influence on the costs in this scenario and this is shown in the Figure 27.

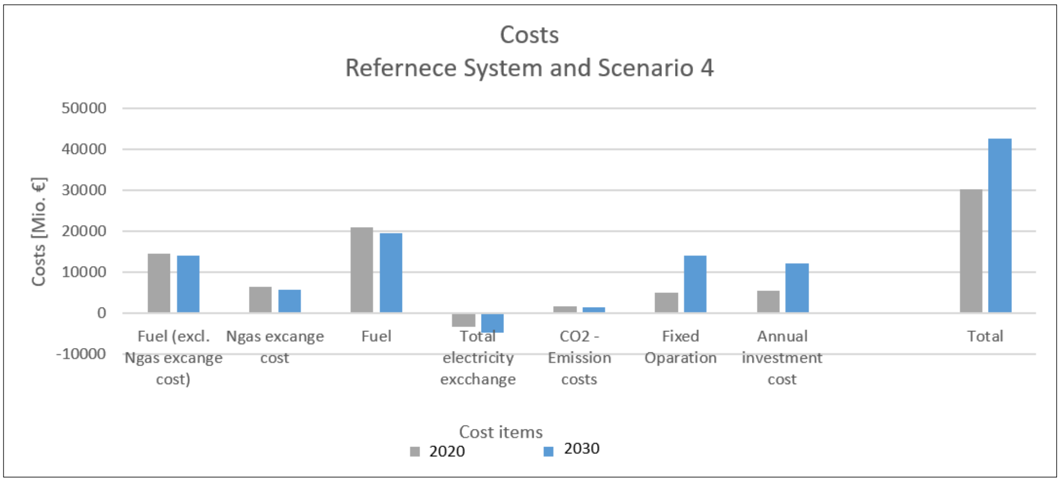



**Figure 27**. Costs -Reference System and Scenario 4

## SCENARIO ANALYSIS

The results of the various scenarios are compared in the following sections.

### *Electricity demand analysis*

Figure 28 shows demand in electricity for the reference system and different scenarios. Demand varies among all these scenarios due to changes in one or another parameter-in all three scenarios, demand increases compared to the reference one.

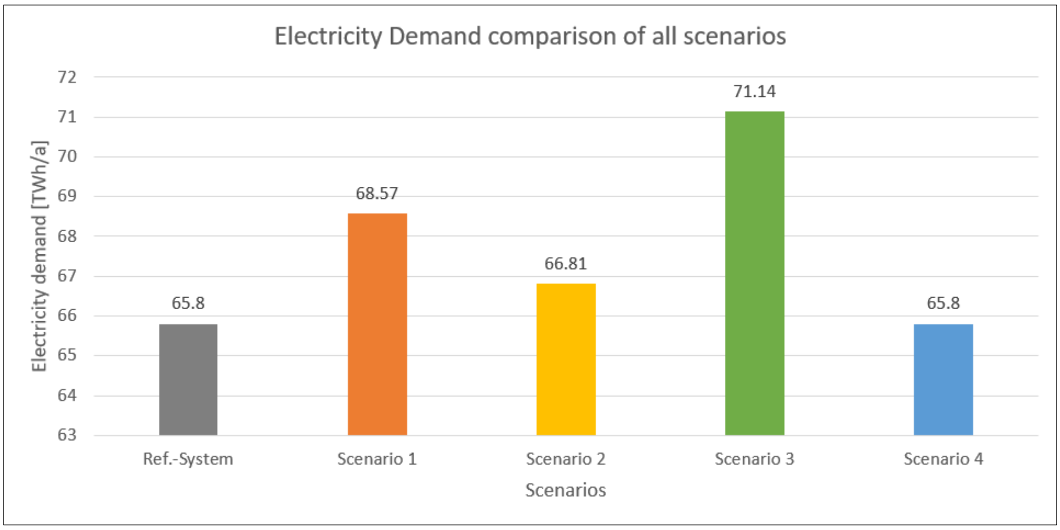



**Figure 28.** Electricity demand analysis for different scenarios

The main reasons for the differing electricity demand in each scenario are as follows.

In Scenario 1, the higher demand is driven by the increased number of electric vehicles, in Scenario 2, it is due to the larger number of heat pumps, and in Scenario 3, the demand is highest due to the hydrogen production via electrolysers. It is expected that, due to learning and scaling effects, electricity demand for electrolysis will decrease slightly between 2020 and 2030 [72]. This increase in demand must be met, ideally, by renewable energy sources. According to the Federal Ministry for Economic Affairs and Climate Protection "Bundesministerium für Wirtschaft und Klimaschutz," future consumption is projected to rise significantly, offsetting the savings achieved through more efficient electricity use in areas like lighting. This increased demand would need to be met by renewable energy sources. Such high consumption is justified by sector coupling, where electricity is used directly (e.g., for electric vehicles) or converted into electricity-based energy sources, such as green hydrogen. Therefore, it can be concluded that Scenarios 1–3 align with projections made by official sources in Germany regarding the future of the energy sector [73]

Scenario 4: The demand for electricity in this scenario remains the same as in the reference system. That was just an assumption in order to focus only on the expansion of the renewable energies. The goal of the case study is to illustrate impacts of the expansion of renewable energies while at the same time shutting down fossil fuel-fired power plants, keeping electricity demand constant. In case of a simultaneous change in demand, comparability with the reference system would have been more complicated. As mentioned above, this is not real and can be considered in further work.

In total, these three scenarios would require an additional 10.74 TWh of electricity. This increased demand could be easily met through the expansion of renewable energy sources, in line with the government's targets outlined in Scenario 4. However, this is not the only increase in consumption expected. In addition to meeting the higher electricity demand across various sectors, there is also the need to gradually replace all non-renewable energy sources.

## *Expansion of renewable energies analysis*

Compared to the reference system, renewables need to be expanded to cover higher demand for electricity in the scenarios 1-3. First, in these three scenarios, only photovoltaic and wind were expanded sufficiently to meet demand. The situation is different in scenario 4. It focused particularly on the expansion of renewable energies-more precisely, photovoltaic, wind, hydro-power, and geothermal power, see Figure 29.

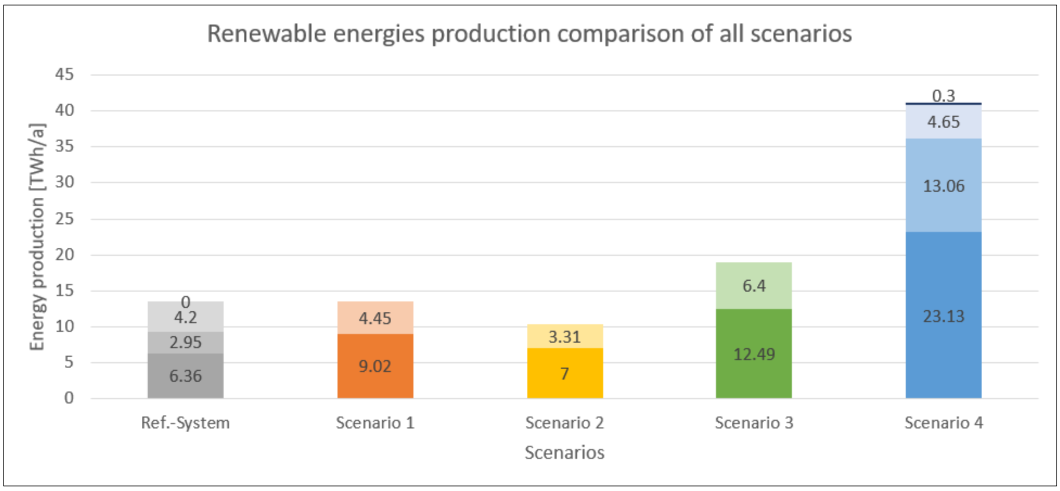



**Figure 29**. Comparison Expansion of renewable energies

Figure 30 shows the development of the expansion targets for renewable energies in Baden-Württemberg.

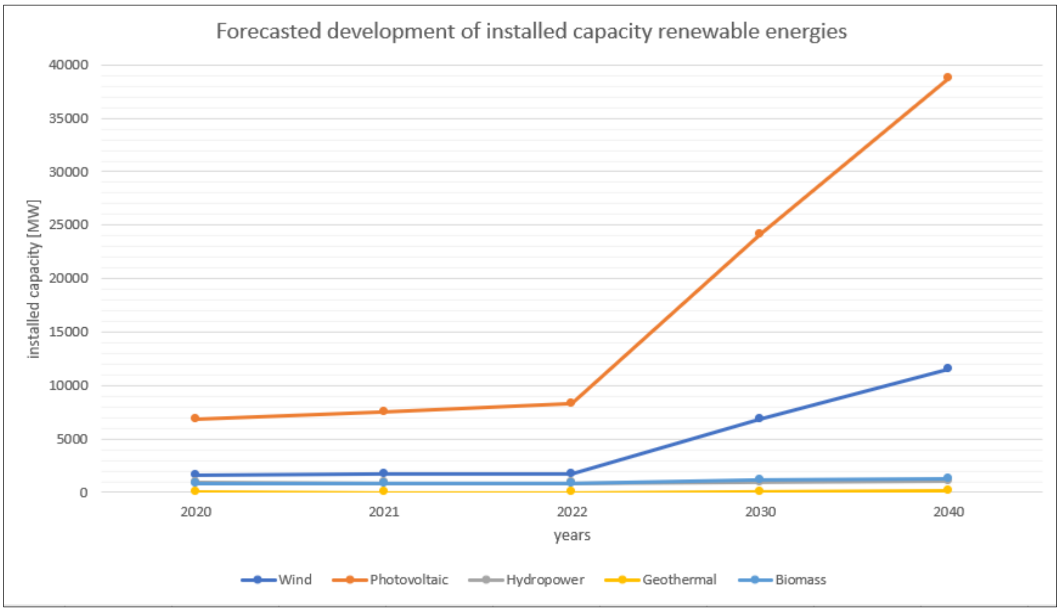



**Figure 30**. Forecasted development of installed capacity renewable energies

The rise of wind power and photovoltaic is remarkable. Over the last three years, the trend has been growing upward, which is not adequate for the target to be reached in 2030. Expansion targets are ambitious, and many measures must be taken over the coming years to achieve these.

Targets, especially those for photovoltaic, are very ambitious. Hence, in August 2023, the German cabinet approved a solar package aimed at accelerating the expansion of ground-mounted and rooftop solar installations, increasing citizen participation. With this package, it was announced that PV would be installed in roughly equal parts on roofs and open spaces. Furthermore, the expansion of Agri-photovoltaic is being targeted, and the expansion on commercial roofs and balcony solar systems is being made less bureaucratic [74].

## *$CO_2$-Emissions analysis*

Since all four of them do aim at reducing $CO_2$-emission, the reduction has been recorded in all scenarios. Among them, scenario 1, especially, where the proportion of electric cars increases as well as the total number of vehicles decreases is really going down. Furthermore, the expansion of renewable energies and simultaneous shutdown of some fossil fuel power plants show a significant reduction in emission. It has to be mentioned that nuclear energy was also reduced, which does not lead to any savings of emissions. In the first three scenarios, this is not the case, so emissions can only partly be compared. Additionally, in the other scenarios, a positive result in terms of emissions can be shown. Therefore, an incredibly huge number of actions with respect to the much too high value of the $CO_2$ has to be taken in order to achieve the goal of climate neutrality by 2045, see Figure 31.

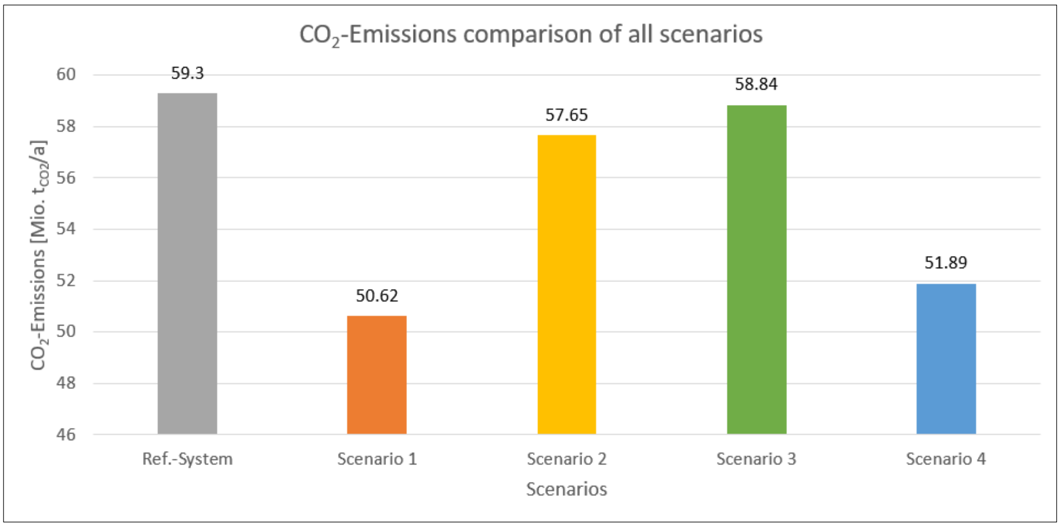



**Figure 31**. $CO_2$-Emissions comparison of all scenarios

## Costs analysis

It has been mentioned in the individual scenarios, the individual technologies and their expansion and decline do have a significant influence on the overall costs. With the overarching goal of reducing $CO_2$-emissions and actively contributing to climate targets, all four scenarios emphasise reducing fossil fuels as far as possible or replacing them with renewable energies. The costs of the different scenarios compared to the reference scenarios are presented in the results section. When comparing the fuels without natural gas, scenario 1 shows the greatest reduction in costs. This is due to the increasing share of electric cars and the simultaneous reduction in conventionally fuelled cars. By dispensing with fossil fuels, the costs related to fuel taxes and general fuel costs are reduced. The same phenomenon can be seen in scenarios 2, 3 and 4. It is also noticeable in scenario 2 that the expansion of electrically powered heat pumps primarily reduces the costs of natural gas. As not all sectors, such as heating, electricity and transport, were considered together in the scenarios and only a partial reduction, based on the federal state's forecasts for 2030, fuel costs remain in all scenarios.

Since Germany and Baden-Württemberg lack sufficient energy and heat supplies, imports are required. The costs for these imports in the reference year were around 3,294 Mio. €. It is remarkable that scenario 4 is the highest in demand for import requirement in Baden-Württemberg since it only involves the electricity sector. This leads to the conclusion that fuels have to be imported from abroad for both the transport sector and especially for the heating sector. The same applies to scenario 1, in which the gradual switch to e-mobility is not sufficient to reduce import costs. Storage systems are suggested to make full use of the energy produced by renewable energies. These have so far been excluded from the current scenarios but may be employed to capture the surplus energy during periods of calm to be produced by variations in renewable energies. This would not be exported as in the scenarios but rather within the home state for security of supply.

In this context, the reduction of fossil fuels and the use and expansion of renewable energies lead to a reduction of $CO_2$-emissions. Accordingly, fewer $CO_2$ taxes and levies have to be paid. This is also reflected in the costs. Consequently, a decrease in the costs of the $CO_2$-emissions can be realized in all four scenarios. Figure 31 shows this under the cost item "$CO_2$-emission costs".

The new technologies applied also result in an increase in fixed operating costs and annual investment costs. The sophisticated technologies require good care and periodic maintenance to maintain the efficiency of the system; fault-free operation and maintenance. The high demands on technological framework conditions over the entire service life led to an increase in costs. One finds especially in scenario 4 a cost increase by the factor of 2.5.

All these factors contribute finally to the overall costs, which can be seen from the different figures in the results section. Besides higher output as such, learning and scaling effects can reduce the specific costs of the respective technologies substantially.

These, however, are massive sums of money that the federal state will have to raise in order to finance the scenarios. With a current state budget for 2023/2024 of 124 billion euros, the proportion required to implement one of the four scenarios would correspond to approx. 25% of the entire state budget [75]. It should be noted that the simulation of the scenarios does not assume any cost changes regarding technologies and taxes in the coming years.

## SUMMARY AND CONCLUSION

The general subject of the article is climate neutrality in Baden-Württemberg, a German federal state. Therefore, four scenarios were elaborated concerning a reference system set in the year 2020, each contributing to reaching climate neutrality by 2045. The simulation of the existing energy system was realized through the EnergyPLAN simulation tool. The simulations showed that in all four scenarios, the use and expansion of renewable energies in conjunction with a reduction of fossil fuels lower the $CO_2$-emissions and therefore make a positive contribution to achieving the climate protection targets. However, it has to be kept in mind that only one sector was considered in each of the individual scenarios. A cross-sectoral approach is required to realize such projects. In addition, sector coupling is recommended in view of the economic efficiency, which can contribute to reducing losses and increasing efficiency as well as lowering costs [72].

Reaching the ambitious goal of climate neutrality in 2045 is a big dream, which requires many steps in planning and realization, one after another. Not least, the length of time necessary for approvals or the acceptance of the population is delaying the expansion of renewable energies. What it needs is action to be taken by politicians in order to reduce or remove such obstacles.

In this regard, expansion toward the attainment of the set targets through the exploitation of renewable energies and green hydrogen can be encouraged through financial incentives. In addition to different bonus concepts, such as feed-in tariff increases, tax rebates, and subsidies, other possible approaches include malus concepts in the form of $CO_2$ taxes levied on the use of fossil fuels. Equalising the costs between renewable energies and fossil fuels can go hand in hand with an increasing willingness to pay and increase the number of potential customers [76]. More importantly, clear legislation on permissions and legal issues reduces the uncertainties over project development and serves to eliminate administrative barriers. Acceleration of the authorisation process also allows the increase in installation rate per year, thus contributing to the achievement of the target.

Moreover, this article also reveals that in all scenarios, high costs are to be expected. However, these costs are likely to come down over the next several years, as research will continue to up efficiency and performance of the technologies and further potential for improvement-mostly for photovoltaics, wind, and electrolysers. In fact, politics is able to create momentum for technical innovation. The provision of funding in the area of research and development with the aim of further reducing costs and increasing efficiency [72]. In addition, the use of storage systems is necessary when using renewable energies. This was neglected in all scenarios. Thanks to storage, energy sources characterised by fluctuations can store the surplus produced for periods of low electricity supply and thus guarantee greater security of supply [72].

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## CONFLICT OF INTERESTS

The authors should confirm that there is no conflict of interest associated with this publication.

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