Navigating the Energy Transition

A Comprehensive Modeling Approach for the Netherlands

EE3L11: Bachelor Graduation Project Electrical Engineering

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by

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Abstract

This report presents an energy transition model that emphasizes the importance of prioritizing innovation. It demonstrates the potential energy savings achievable through the installation of insulation layers. Additionally, it explores the increasing adoption of electric vehicles (EVs) and its influence on energy consumption within the transportation sector. The report also discusses renewable energy sources and explores energy storage methods. Lastly, the report concludes by highlighting the need for a balance between energy supply and demand, acknowledging that traditional energy sources will continue to be necessary in 2030, aligning with expectations. This comprehensive analysis serves as a foundation for future research endeavors aimed at developing a more precise model

Preface

This report is a component of the Bachelor Graduation Project within the Electrical Engineering Programme at TU Delft. Some of the sub-models utilized in this project involve calculations and simulations that rely on custom-built code in Matlab. This thesis aims to contribute to the ongoing dialogue and efforts surrounding the energy transition, providing valuable insights and paving the way for innovative solutions. We present this thesis with pride and a sense of responsibility, knowing that it represents our commitment to making a positive difference in the world.

We would like to express our sincere appreciation to Dr. M. Cvetkovic, our supervisor, for his assistance during this project. We also like to thank Delft University of Technology's Faculty of Electrical Engineering, Mathematics, and Computer Science (EEMCS) for providing the essential tools and a conducive environment for study.

Anass Akaouche & Muasser Hameed
Delft, July 2023

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1 Introduction

1.1. State of the art analysis

"The Illuminator Energy System Development Kit" presents a comprehensive exploration of energy transition through the development of a replicable, low-fidelity toolkit. The focus of the simulations in this kit is primarily on the present-day energy system, aiming to demonstrate system-level integration, its challenges, and potential solutions. The simulations conducted in this study provide valuable insights into the current state of energy transition and serve as an inspiration for further research and modeling in the field.

The simulations in the Illuminator toolkit utilizes a co-simulation approach, allowing for the integration of various energy system components and the examination of their interdependencies. This approach aims to facilitate interactions among domain experts, educate students and communities, and foster communication within the energy transition. These simulations have provided valuable insights into the challenges and opportunities of the present-day energy system. They have emphasized the importance of system-level integration and the need for effective communication and collaboration among stakeholders in the energy transition. This type of modeling has inspired us into doing the same for future scenarios. In conclusion, the simulations conducted in the illuminator toolkit have contributed to the understanding of the challenges and opportunities in the present-day energy system. They have inspired further research and modeling in the field of energy transition in the future [60].

1.2. Problem definition

The Netherlands has historically relied on traditional energy and in particular natural gas as a key component in its energy mix and overall economic success. While such dependence proved beneficial at first, growing concerns regarding environmental effects coupled with limited resources necessitate greater innovation towards more sustainable practices.
In a determined effort to move towards more sustainable sources of energy, the Netherlands has adopted a proactive approach. By analyzing various sectors like buildings and transportation and resolving their respective energy demands through green sources, it hopes to decrease greenhouse gas emissions while increasing the share of renewable energy and increasing energy efficiency. External factors such as political stability, market dynamics, and recent events like the COVID-19 pandemic and the conflict between Russia and Ukraine, have had a significant impact on the energy transition, especially in the Netherlands. These factors can introduce uncertainties and fluctuations in the energy market, shaping the trajectory of the transition and influencing decision-making processes as it will also impact some decisions made in this report.
The Netherlands aims to achieve a future where energy is generated from sustainable sources and contributes to a low-carbon economy. The country has established targets, such as reducing greenhouse gas emissions by a certain percentage (e.g., 49% or 55% for the extended package by 2030 compared to 1990 levels) and increasing the share of renewable energy in the overall energy mix. The transition

involves considering technical feasibility, economic viability, legal frameworks, political support, cultural acceptance, and social engagement.
The necessity of a comprehensive energy transition model can be approached from various perspectives.

- Energy security: The political tensions between Russia and Ukraine highlight the risks of relying on a single energy source. The Netherlands needs to diversify its energy sources to ensure energy security and reduce vulnerability to geopolitical tensions.
- Environmental and climate considerations: The energy transition aims to address environmental challenges and combat climate change. Shifting to renewables helps mitigate greenhouse gas emissions, air pollution, and environmental degradation.
- Global energy transition trends: International agreements and commitments, such as the Paris Agreement, drive the transition to low-carbon energy systems. The political tensions can further motivate the Netherlands to align with global energy transition trends and contribute to a sustainable future.

The objective is to provide end-users with a clear understanding of the tangible adjustments required to achieve the set goals for 2030. This comprehensive report aims to demonstrate that while the energy transition will necessitate effort, it is highly achievable. It is designed to instill confidence in individuals, empowering them to address the challenges of the energy transition in practical terms by implementing our proposed ideas.
The energy transition project in the Netherlands operates within constraints, such as regulatory, economic, and technological limitations, these limitations must all be respected. It allows flexibility in parameters like the energy mix, such as other forms of renewable energy that is not discussed in this project. In the coming years, the validity of the model's results can be confirmed by measurable factors such as greenhouse gas emissions, wind and solar capacity, energy efficiency, and public acceptance.

1.3. Structure of the document

This thesis primarily focuses on the methodology and approach used in modeling innovation in energy demand, as discussed in chapter 3. It also explores the supply of renewable energy and its projected capacity for 2030, which is elaborated on in chapter 4. Additionally, the thesis examines energy storage methods and assesses the potential for energy storage by 2030, this is discussed in chapter 5. Subsequently, the import and export of energy is looked at in chapter 6. Finally, the findings are analyzed and discussed, leading to a conclusion that includes recommendations. The flow diagram presented below provides an overview of the concept explored in this thesis.

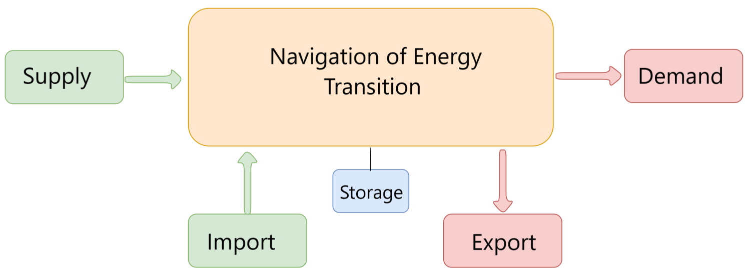

Figure 1.1: Overview for this thesis

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Program of Requirements

In this section, we will discuss the design criteria for energy demand, supply, storage, and import/export. The mandatory requirements must be fulfilled to ensure the validity of the project, while the trade-off requirements will be addressed if time allows. These trade-off criteria will enhance the precision and accuracy of the design.

2.1. Design Limitation

The time constraint is a significant limitation for this project, as it restricts the extent of activities that can be undertaken. Consequently, certain models will need to be simplified in order to create an accurate model within the given time frame. Additionally, the involvement of the agriculture sector is not taken into account, as its energy demand is not expected to have a significant impact on the overall demand and supply values. Furthermore, the issue of energy grid congestion is not considered, despite its potential impact when installing additional capacity for renewable generation. Moreover, the project does not take into account government policies and sound economic factors.

Mandatory Requirements

1. The energy transition thesis must ensure that the renewable energy generation goals fulfill the requirements of the base 49% package (for electricity generation) outlined in the climate agreement. Specifically, the thesis should aim to generate a minimum of 49 TWh from offshore wind and 35 TWh from renewable sources on land;
2. The thesis should adhere to the renewable energy generation goals specified in the climate agreement's 55% package. It is crucial not to exceed the limit of 120 TWh from renewable energy, as exceeding this threshold would render the model unrealistic.

Trade-off requirements

1. The export of energy abroad should only occur when the country has surplus energy that exceeds its domestic consumption and after fully utilizing available storage options;
2. The thesis should consider modeling the reduction of CO_2 emissions for each sector due to innovation in that sector;
3. Enhance the accuracy of the energy transition thesis by incorporating active wind speeds and solar irradiance data every 15 minutes throughout the year 2030. This approach moves beyond relying solely on average figures, providing a more precise representation of the fluctuating conditions that impact renewable energy generation.

3 Demand

The chapter is divided into three main sections: transport, buildings, and industry. The buildings section examines the energy demand of residential and non-residential buildings in the Netherlands, considering factors such as physical footprint and energy requirements. The transport section focuses on modeling energy demand and CO2 emissions for electric and fossil fuel vehicles, aiming to close knowledge gaps and improve decision-making. The industry section analyzes the energy demand for natural gas and electricity consumption. Overall, the demand chapter provides a comprehensive analysis of energy demand patterns across different sectors, which is crucial for effective energy planning and transition strategies.

3.1. Buildings sector

The energy demand of buildings in the Netherlands is a crucial aspect of the country's sustainability efforts. With a strong focus on reducing greenhouse gas emissions, the Dutch government and stakeholders are actively working towards creating a more energy-efficient and sustainable built environment. When examining the overall energy consumption in the buildings sector, it is crucial to consider numerous factors that can impact the demand for energy, both on a daily and yearly basis. It is important to acknowledge that various types of buildings exist, each with distinct energy requirements. The primary differentiation lies between residential and non-residential buildings. These two categories differ significantly from each other in several ways. Firstly, there is a higher number of residential buildings compared to non-residential buildings in the Netherlands. Secondly, non-residential buildings typically have a larger physical footprint, resulting in greater energy usage compared to individual residential households. Therefore, it is vital to recognize and understand the disparities between these types of buildings.

3.1.1. Residential sector

In order to ensure the accuracy of the modeling of total energy demand in 2030 within the residential sector, it is necessary to consider the subdivision of household types. Five distinct building types are distinguished: apartments, corner houses, terraced houses, semi-detached houses, and detached houses. Each of these building types possesses unique characteristics and architectural data. These differences are significant as they directly impact the potential energy savings that can be achieved per building. Therefore, accounting for these variations is crucial to enhance the precision of the model.

Methodology

Upon analyzing the global and specifically Dutch building profiles and energy consumption, it is evident that between 2013 and 2021, there was a notable decrease in the final energy demand within households. The demand decreased from slightly below 450 petajoules (PJ) to slightly above 400 PJ as is depicted in figure 3.1. The total energy demand in buildings encompasses various applications where energy is consumed, such as space heating, cooling, cooking, and lighting, among others. The goal is to identify ways to improve these appliances so that they consume less energy in 2030 compared to the present. Analyzing the data reveals that more than 70% of the total energy demand in buildings is attributed to space heating. Therefore, focusing on innovations that reduce the need for space heating in households will have a substantial impact on energy savings compared to innovating other energy-consuming appliances. Consequently, the decision has been made to solely consider improvements in insulation levels in buildings, assuming that no other appliances will be innovated until 2030, apart from insulation. This approach excludes the adoption of electric heaters or hydrogen-based hybrid heat pumps. This choice is motivated by the challenges associated with implementing these technologies on a large scale, including concerns about performance in colder climates, maintenance costs, operational expenses, and the lack of incentives for citizens to invest in heat pumps, which hampers their widespread adoption. When establishing goals for enhanced insulation in buildings, the inclusion of air-to-air heat pumps will also be considered. Consequently, the modeling of final energy consumption in the buildings sector will solely focus on improvements in insulation, the utilization of air-to-air heat pumps, and the installation of solar panels on rooftops. These factors are chosen due to their potential to contribute to energy efficiency and sustainability in the building sector.

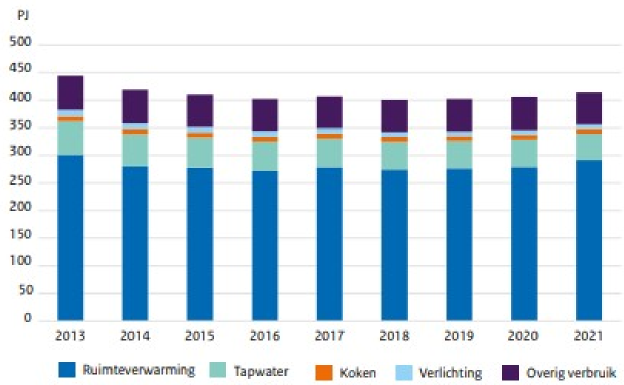

Figure 3.1: Final energy consumption in households by function, in Petajoules [56]

Innovation in insulation

The thermal efficiency of a building can be measured using a parameter called the U-value, which is the reciprocal of the R-value. The R-value also known as thermal resistance is significant because specific architectural data is provided in R-values, while calculations are conducted using U-values. The U-value, also known as thermal transmittance, quantifies the rate at which heat transfers through a wall, window, or any other structure. It is measured in units of watts per square meter per Kelvin ($\frac{W}{m^2K}$). A high U-value indicates poor insulation while improving insulation reduces this value. The U-value takes into account heat loss caused by conduction, convection, and radiation [50]. One of the goals that can be set as a requirement for new homes in the Netherlands, as outlined in the EPISCOPE partner DUT report (3.14), is to establish specific insulation standards for walls, roofs, and windows to enhance thermal performance and reduce heat loss [24]. In contrast to the EPISCOPE model, which focuses solely on setting requirements for newer buildings, the model described in this context also utilizes the mentioned numbers for existing buildings. This deviation arises from the recognition that there is still potential to improve upon existing homes, which is not explicitly addressed in the EPISCOPE paper. A comprehensive approach to enhance insulation in the buildings sector is also discussed in another paper [12]. It proposes that incorporating a 20cm layer of insulation in attics and roofs alone could potentially lead to a significant reduction of 14% in the energy demand of buildings. This measure underscores the substantial impact that insulation improvements can have on energy efficiency and sustainability in the built environment.

Calculation and results

The formula

$$\text{Energy Saved (in a year)} = (U_1 - U_2) \times A \times \text{HDD} \times \frac{24}{1000}$$

is employed to calculate the amount of energy that can be saved as a result of insulation measures. Where:

- $U1$ is the initial U-value (measure of heat transfer) of a building component.
- $U2$ is the final U-value of a building component after improvement.
- A is the surface area of the building component.
- HDD is the heating degree days.
- $24/1000$ is the conversion factor to kWh.

By utilizing this formula, it is possible to estimate the energy savings achieved through insulation improvements over the course of a year.
In accordance with the ambitious nearly Zero Energy Building (nZEB) standard mentioned in [24], the value U2 is assumed to adhere to this standard. The specific values for U1, as well as the values for each building type utilized in this model, are sourced from the reference documents provided by [40]. These sources provide the necessary data to incorporate accurate U-values for different building types and facilitate precise calculations in the model.
As stated in the document, the specific characteristics for each building type, including the thermal envelope area, are provided. An example of a corner house can be viewed in figure 3.2. The thermal envelope area (the loss area) is calculated specifically for apartment buildings, while for other building types, this information is already presented in the architectural data table. Furthermore, the concept of heating degree days (HDD) is introduced, which is a metric used to estimate the energy needed for heating a building. HDD is determined by measuring the cumulative number of degrees by which the average daily outdoor temperature falls below a base temperature, typically representing the threshold at which heating is required. This metric allows for a quantitative assessment of the energy demand for heating purposes based on the prevailing climate conditions.
Referring to the graph provided by the IEA [36], it showcases the heating degree days in the Netherlands over the past 20 years. By employing the linear regression model depicted in the figure, a prediction can be made for the heating degree days in 2030, which is estimated to be 1984 HDD (calculated as

$$\text{Result} = 2054 - \left(\frac{7}{\text{year}} \times 10\text{years}\right)$$

), based on a base temperature of 16 degrees Celsius.

To complete the calculation for the reduced energy demand resulting from insulation, the total number of buildings and the distribution of building types were taken into account. It is mentioned that there were 8063493 residential buildings in the Netherlands, which further aids in determining the overall impact of insulation improvements on energy consumption within the building sector [66]. Based on the distribution of building types outlined in the document provided, [40], it is estimated that the energy savings in 2030 resulting from insulation improvements will amount to 10.70 PJ.
Considering that the energy used in residential buildings in the Netherlands in 2020 was 383810 TJ, as reported by the International Energy Agency (IEA) [38], it can be inferred that the final energy consumption for the residential sector in the Netherlands in 2030 is projected to be 373111 TJ. The calculations can be found in Appendix A.

	Variant met Zelfregelende roosters
Rc-waarde gevel	5,0 m²K/W
Rc-waarde dak	5,0 m²K/W
Rc-waarde begane grondvloer	5,0 m²K/W
U-waarde ramen	1,65 W/m²K
U-waarde voordeur	2,0 W/m²K
Buitenzonwering op	W

(a) Architectural data corner house [40]

Kenmerk	Waarde
Beukmaat	5,1 m
Woningdiepte	8,9 m
Verdiepingshoogte	2,6 m
Gebruiksoppervlakte A_g	124,3 m³
Verliesoppervlakte $A_{verlies}$	230 m²
Verhouding $A_g/A_{verlies}$	0,5
Gemiddelde gebruiksoppervlakte in MNW	125,0 m²

(b) Characteristics of a corner house [40]

Figure 3.2: Building data for a corner house

3.1.2. Non-Residential sector

In the modeling approach for the commercial sector, a simplified assumption is made that all non-residential buildings belong to one type, specifically the office building described in [40]. Due to the limited availability of information regarding the distribution of building types in the commercial sector, the same Nearly Zero Energy Building (nZEB) standards used for residential buildings are applied to the non-residential sector. However, it is important to note that this simplification may lead to inaccuracies, as there is likely significant variation in building types within the non-residential sector. Additionally, the nZEB standards were primarily designed for residential buildings and may not be fully applicable or representative for the commercial sector. Based on these assumptions, the model calculates a final consumption of 176659 TJ for the non-residential/commercial sector, indicating energy savings achieved through improved insulation. However, it is essential to interpret this number with caution, considering the limitations mentioned above, which can introduce significant skewness to the results.

3.2. Transport sector

3.2.1. Electric vehicles and fossil-fueled cars

Electric vehicles

1. Introduction to innovation

Global energy consumption and carbon emissions are significantly influenced by the transportation industry. The majority of cars on the road today are fossil fuel-powered, with conventional fuelling facilities. But the introduction of electric cars (EVs) has brought about a disruptive innovation that promises to change the way people travel in the future [29].
Electric vehicles are a more environmentally friendly alternative to conventional combustion engine vehicles, representing a paradigm change in the automobile industry. As it stands, EVs are gaining pace and challenging the dominance of fossil fuel automobiles .

2. S-curve modelling

Due to the fact that electric vehicles are new innovations in the automotive sector, it is anticipated that their growth would follow an S-curve pattern. A typical growth pattern seen in the acceptance of new inventions or technology is the S-curve.

The S-curve is characterized by three stages:

1. At the initial stage of EV adoption, known as the ”emergence stage,” the market penetration is relatively low as the technology is new and unfamiliar to consumers. Innovators and early adopters, who are individuals with a high propensity for embracing new technologies, play a significant role in driving the adoption of EVs at this stage. Innovators are the first to adopt the technology, often driven by their curiosity and willingness to take risks. Early adopters are opinion leaders who follow the innovators;

2. As the EV industry picks up steam and moves into the ”acceleration stage,” the growth rate begins to quicken. Consumer demand is growing, the government is supporting the transition to electric vehicles, and there is beneficial legislation in place. At this point, a bigger segment of the market, the early majority, and late majority, start adopting EVs. The early majority is made up of people who accept a technology after the early adopters have proven it, and who are motivated by the need to preserve their social standing and avoid risks. The late majority adopts technology after the early majority but often does so more reluctantly;
3. Once EV adoption hits a certain level, it enters the ”saturation stage,” during which the growth rate begins to stabilize. The S-curve’s mature stage is represented by this phase. As EVs become more commonplace and consumers have access to a wider selection of vehicles, the market penetration is pretty high. As the industry nears saturation with a sizable number of customers either having an EV or anticipating getting one soon, growth may slow down at this point. The remaining group in this stage may consist of laggards, who are people who are slow to accept new technology;

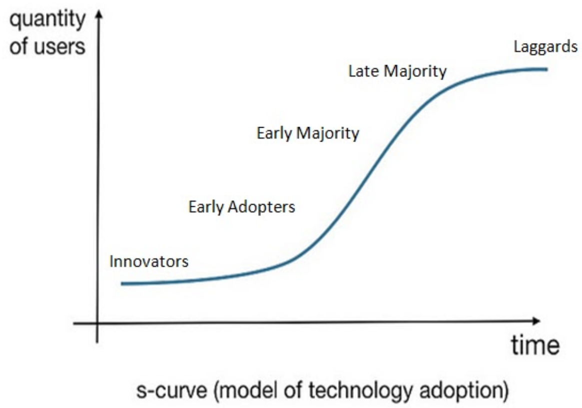

Figure 3.3: This figure represents a theoretical S-curve for technological innovations with its 3 stages and actors [53]

Fossil Fueled Cars

1. Introduction to Fossil Fuel Cars

- Fossil fuel vehicles have dominated transportation but are now facing a shift towards sustainable and electric alternatives due to environmental concerns. Fossil-fuel vehicles have a significant environmental impact through emissions and air pollution, emphasizing the need for cleaner alternatives like electric cars. Accurate energy predictions for fossil fuel vehicles in 2030 are vital for planning renewable energy infrastructure and promoting cleaner alternatives, addressing climate change, and improving air quality.

2. Explanation of ARIMA Modeling

- ARIMA also known as (AutoRegressive Integrated Moving Average) is a popular statistical method for time series analysis and forecasting. It is a combination of three components: autoregressive (AR), integrated (I), and moving average (MA). ARIMA models are flexible and can capture both the linear and non-linear patterns present in time series data.
- The components of ARIMA are defined as follows:

  Autoregressive (AR): The autoregressive component models the linear dependence between an observation and a certain number of lagged observations. It assumes that the current value of a time series is influenced by its past values. The p parameter in ARIMA(p, d, q) represents the order of autoregressive terms.

The equation for the AR component is:

$$y(t) = c + \phi_1 y(t-1) + \phi_2 y(t-2) + \ldots + \phi_p y(t-p) + \varepsilon(t)$$

where: $y(t)$ represents the value of the time series at time t. c is a constant term. $\phi_1, \phi_2, \ldots, \phi_p$ are the autoregressive coefficients for lag 1, lag 2, ..., lag p, respectively. These coefficients in MATLAB are just the slopes at certain times, $\varepsilon(t)$ is the error term.

Integrated (I): The integrated component accounts for the differencing needed to make the time series stationary. Stationarity refers to a time series having a constant mean, constant variance, and autocovariance that does not depend on time. Differencing involves taking the difference between consecutive observations to remove trends or seasonal patterns. The d parameter represents the order of differencing.

The equation for the I component is:

$$\Delta y(t) = y(t) - y(t-d)$$

where: $\Delta y(t)$ represents the differenced value of the time series at time t. $y(t)$ represents the original value of the time series at time t. d represents the order of differencing.

Moving Average (MA): The moving average component models the dependency between an observation and a residual error from a moving average model applied to lagged observations. The moving average terms capture the short-term fluctuations in the time series. The q parameter represents the order of moving average terms.

The equation for the MA component is:

$$y(t) = \mu + \theta_1 \varepsilon(t-1) + \theta_2 \varepsilon(t-2) + \ldots + \theta_q \varepsilon(t-q) + \varepsilon(t)$$

where: $y(t)$ represents the value of the time series at time t. μ is the mean of the time series. $\theta_1, \theta_2, \ldots, \theta_q$ are the moving average coefficients for lag 1, lag 2, ..., lag q, respectively. $\varepsilon(t)$ is the error term. [10]

3. Justification for ARIMA Modeling

A pragmatic approach is adopted for forecasting energy demand, utilizing the flexibility offered by ARIMA models. The focus is on incorporating significant factors such as the increasing adoption of electric vehicles (EVs) and the implementation of government regulations targeting the phasing out of fossil fuel cars. The ”play buttons” of the autoregressive (AR), integrated (I), and moving average (MA) components are employed, allowing for an iterative trial-and-error methodology to refine the predictions.

The AR component assumes a critical role in the analysis by establishing a link between historical energy demand patterns and past values. This linkage captures the correlation between the present and the past, facilitating the modeling of long-term trends and their anticipated impact on future energy demand.
The integrated (I) component proves to be highly valuable in removing patterns that may be present in the data. Through differencing the time series, the focus shifts to isolating the remaining fluctuations and random components, enabling a clearer understanding of the underlying dynamics governing energy demand.
Additionally, the moving average (MA) component offers practical advantages in capturing short-term irregularities influenced by various factors, including the adoption rate of EVs or seasonal variations. By incorporating the MA terms, the model can effectively capture and forecast these short-term fluctuations, leading to a more comprehensive analysis of energy demand dynamics.

In this context, relying solely on the upcoming influences on fossil fuel cars to predict energy demand in 2030 would not be sufficient, as it lacks a comprehensive trend analysis. This is where ARIMA comes into play as a valuable tool. ARIMA, with its autoregressive, integrated, and moving average components, offers the necessary framework to incorporate trend analysis. It serves as a helping tool to augment the forecasting process and provide a more accurate understanding of energy demand dynamics. By combining factual information on upcoming influences with the analytical capabilities of ARIMA, a more robust prediction for energy demand in 2030 can be achieved.

3.2.2. Results and Findings

Electric vehicles

The Netherlands has emerged as a frontrunner in promoting electric mobility, indicating that the country has progressed beyond the initial stage and is now in the accelerating phase of electric vehicle (EV) adoption. In 2020, around 25% of new cars sold in the Netherlands were electric, highlighting a significant market share for EVs [68]. The government's proactive approach in providing tax benefits, subsidies, and investing in charging infrastructure development has played a pivotal role in encouraging EV adoption. These measures have attracted a considerable number of customers who are characterized as innovators and early adopters [9].

In a study [51] where energy research and social science are combined it has become evident that factors that influence attraction to EVs are:

- purchase cost
- driving range
- recurring purchases: When a particular type of automobile is offered, a certain percentage of car customers always buy it.
- Social reasons: Wanting to blend in or stand out from others.

In 2030, the acceleration phase of electric vehicle (EV) adoption is still applicable due to several factors outlined in the article.
One of the factors influencing the uptake of EVs is the purchase cost. Falling battery costs will push EVs to price parity and beyond between 2025 and 2029, depending on the segment. This indicates that by 2030, the cost of EVs is expected to decrease, making them more affordable for a larger portion of the population.This reduction in purchase cost encourages more consumers to adopt EVs, contributing to the acceleration phase [64] [8].
The range of EVs is another aspect. By 2030, the typical electric car on the road will have a range of roughly 440 kilometers which is a significant difference compared to the range of 300 kilometers registered in 2020. As the driving range increases, it reduces a potential purchaser's worry, making EVs a more practical alternative for daily use. The adoption of EVs will accelerate in 2030 thanks to the constant increase in range [14].
The adoption of EVs is influenced by societal variables. A specific percentage of automobile customers always purchase the same kind of vehicle when it is offered. The early and late majority stages of the adoption curve are represented by this behavior. As EVs grow rapidly on the market, people may prefer to buy EVs over gasoline-powered vehicles because of a desire to blend in. The combination of decreasing costs, improved range, and social factors indicates that the accelerated growth and adoption of electric vehicles will continue in 2030. These factors support the ongoing S-curve growth pattern, leading to higher adoption rates and market penetration of EVs. This can clearly be seen in figure 3.4.
To calculate the energy a dataset of registered electric vehicles starting from 2017 till 2023 is conducted [59]. These numbers have been converted to energy in the following manner:

Given:

$$\text{average\_consumption} = 684000 \text{ J/km}$$

$$\text{average\_km} = 11000 \text{ km}$$

$$\text{total\_energy\_usage} = \text{evs} \times \text{average\_consumption} \times \text{average\_km}$$

- EVs represents the amount of registered electric cars from the years 2017 till 2023 [59].
- Average consumption represents the consumption of a typical electric vehicle in the Netherlands [19].

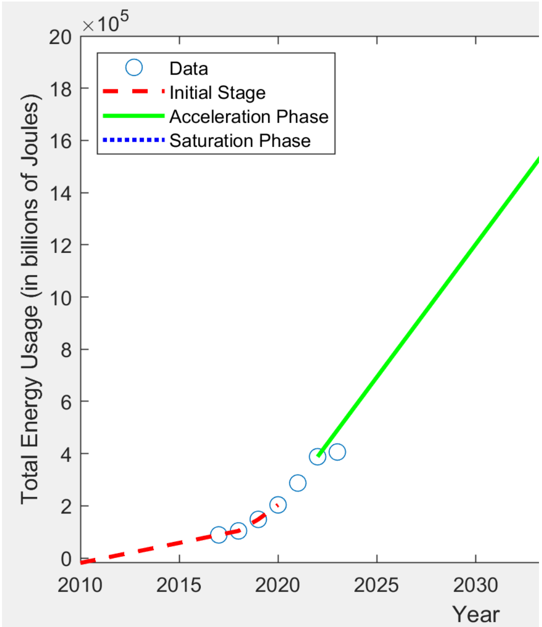

Figure 3.4: This figure shows the energy usage or demand in billions of Joules, fundamentally this is based on registered EVs from the years 2017 till 2023 and then converted to energy [59].

- Average km refers to the average mileage someone from the Netherlands drives on a yearly basis [44].

The determination of the green slope for the acceleration phase (specifically for the years 2020 to 2022) was conducted to quantify the rate of change in energy usage. Extrapolation analysis was employed to establish a connection between the data points of EVs between 2020 and 2022 and estimate the trend, ultimately determining the slopes. The following step-by-step method was employed to obtain the specific slopes: Firstly, the years corresponding to the data points were defined, where 2020 was considered as year 1, 2021 as year 2, and 2022 as year 3. Next, the energy usage data points were converted to billions of joules by dividing each data point by 10^9, resulting in billions of joules. To perform extrapolation analysis, the trend observed in the data points was extended beyond the available data range to estimate the future values. By assuming that the existing increasing trend would continue, the specific slopes were determined by calculating the rate of change in energy usage per year. The reason for selecting the years 2020 to 2022 was due to the already increasing manner in energy usage. By analyzing this period, one can capture and quantify the ongoing growth in energy usage. Extrapolation has allowed to extend the trend and make informed predictions regarding the energy usage trajectory.

Hence, by combining all the mentioned concepts and techniques it can be concluded that the projected energy demand in 2030 for EVs equals 1202180 billion Joules.

Fossil fueled cars

1. Energy Trend of Fossil Fuel Cars

- The trend of the historical energy demand is obtained by firstly obtaining the fossil fuels consumed in billions of kg from CBS. The following implementations have been done to display the historical trend to energy in Joules.

    1. At first, the volume of the respective fossil fuels was calculated by dividing the masses by

their respective densities, as shown below:

$$\text{volume\_benzine} = \frac{\text{benzine}}{\text{density\_benzine}}$$
$$\text{volume\_diesel} = \frac{\text{diesel}}{\text{density\_diesel}}$$
$$\text{volume\_lpg} = \frac{\text{lpg}}{\text{density\_lpg}}$$

2. Then, the energy was calculated by multiplying the obtained volumes by the combustion heats of the respective fossil fuels, as shown below:

$$\text{energy\_benzine} = \text{volume\_benzine} \times \text{combustionheat\_benzine}$$
$$\text{energy\_diesel} = \text{volume\_diesel} \times \text{combustionheat\_diesel}$$
$$\text{energy\_lpg} = \text{volume\_lpg} \times \text{combustionheat\_lpg}$$

Eventually figure 3.5 was derived from implementing the above conversions.

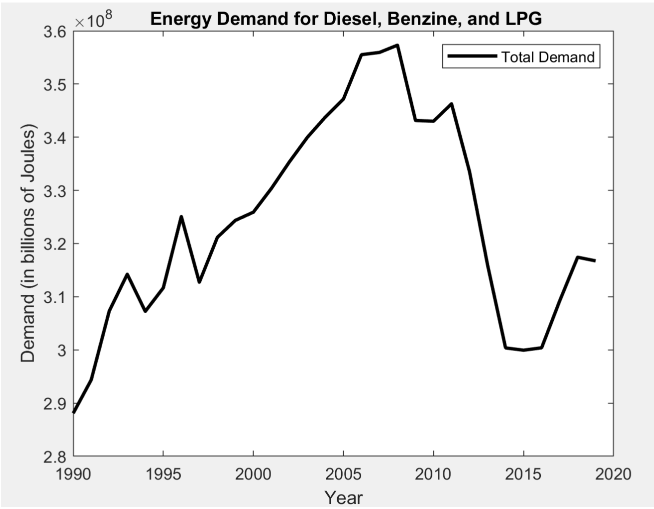

Figure 3.5: The graph indicates a rising trend in energy demand until 2008, followed by a notable decline caused by the economic crisis of that year. After a period of economic stabilization, energy demand experienced a subsequent increase in 2016. [15]

The graph shown here illustrates a significant increase tendency in energy demand up to 2008. However, because of the severe effects of the economic crisis that developed during that year, there was a significant decline that followed. The effects of this crisis rippled over the whole world economy, resulting in an extended period of instability and impeding the rise of the energy demand. However, as the years went by and the economy began to stabilize again, a comeback in energy consumption became apparent in 2016, indicating a return to more ordinary circumstances.
The integration of trend analysis into the justification for ARIMA modeling is crucial for capturing and forecasting future energy demand patterns. By considering the historical data, it is important not to overlook natural trends in order to obtain accurate predictions.
To ensure the validity of the analysis, the abnormal year of 2020, impacted by the COVID-19 pandemic, has been excluded. Unlike the severe and prolonged recovery period following the 2008 economic crisis, the economy rebounded relatively quickly after 2020, returning to a healthy state. Thus, it is plausible to assume that energy demand started rising immediately after the pandemic ended and will continue to grow, as it did prior to the crisis.
However, it is essential to acknowledge that the pace of growth may differ compared to the pre-2008 period due to certain factors. Firstly, there was a slight saturation period observed in 2019 before the pandemic, limiting the growth rate. Additionally, the introduction of electric vehicles in 2010, coupled with their rapid rise since 2017, has impacted energy demand patterns. EVs are gaining increasing

traction due to government policies and additional advantages, leading to a growing market share. Looking ahead, by 2025, EVs are projected to reach price parity with fossil fuel cars, while also improving in range and efficiency. This will result in a slower growth rate after 2025. The ARIMA model, specifically using parameters (3,1,3), incorporates these considerations.
The autoregressive (AR) part is set to 3, considering the years 2019, 2018, and 2017, as there was already a rising trend since 2016, and 2020 was an anomaly that disrupted this ongoing trend.
The differencing (I) part is implemented to remove the general rise observed from 2017 to 2019 and smoothen the trend. Through trial and error, a slower growth rate after 2025 was achieved, aligning with the aforementioned factors that contribute to decelerated growth.
Finally, the moving average (MA) part is set to 3 to account for short-term irregularities influenced by various factors, such as the economic crisis in 2008.

In summary, the combined effect of these modeling choices results in a rising curve representing two distinct periods: the continuation of the trend after the 2020 COVID-19 period, which began in 2016, and a significantly slower growth rate observed after 2025, leading to energy demand of 322.9 PJ. Figure 3.6 illustrates these findings.

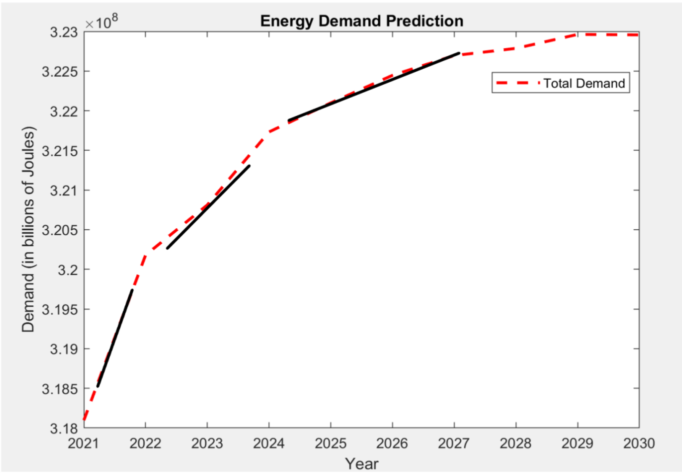

Figure 3.6: Integration of trend analysis into ARIMA modeling for forecasting energy demand, considering historical data, exclusion of anomalous years (e.g., 2020), and the impact of factors such as the 2008 economic crisis and the rise of electric vehicles.The resulting model captures the rising trend pre-2020, a slower growth rate after 2025 which can be derived from the slopes, and incorporates autoregressive (AR), differencing (I), and moving average (MA) components.

2. CO2 Trend of Fossil Fuel Cars

The CO2 emissions have been calculated using the carbon intensity factor to convert the energy demands calculated from the previous section to CO2 emission. The carbon intensity factor directly correlates energy consumption and CO2 emissions. It quantifies the amount of CO2 emitted for each unit of energy consumed, allowing for a straightforward conversion. The carbon intensity factors yield:

- 371 g/kWh for EVs [13].
- 476.2 g/kWh for fossil-fueled cars [61].

Consequently, because the energy demand is calculated in Joule the conversion factors are adjusted by converting them to kg/J. The code in the appendix A demonstrates exactly how the conversion was done. Thus the obtained trends for the CO2 emission of EVs and fossil fuel cars are shown in figure 3.7 and 3.8. However since the data has only been plotted till 2020, the value of 29.8 billion kg of 2021 [30] has been used as a correction factor to the model in the following manner: The code in appendix A adjusts the fossil-fuel cars data to align with the real-time value for 2021. It then recalculates the CO2 emissions using the adjusted data. Linear regression is performed to estimate the growth rate of the adjusted emissions data. The emissions are re-scaled to start from the real-time value for 2021, and

the growth rate is applied to the subsequent years. The adjusted emissions data is plotted over the years 2021 to 2030.
This ensures that the adjusted data starts with the real-time value and maintains the same (approximated) trend as the original data. leading to a CO_2 emission value of 30.1889 billion kg in 2030.

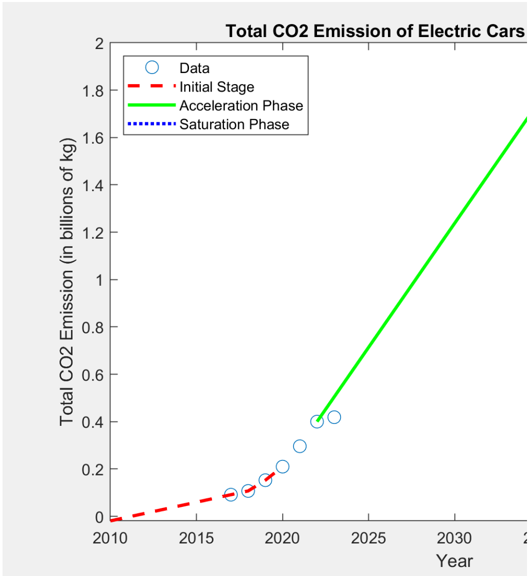

Figure 3.7: This figure represents a direct conversion from energy usage to CO_2 emission of EVs

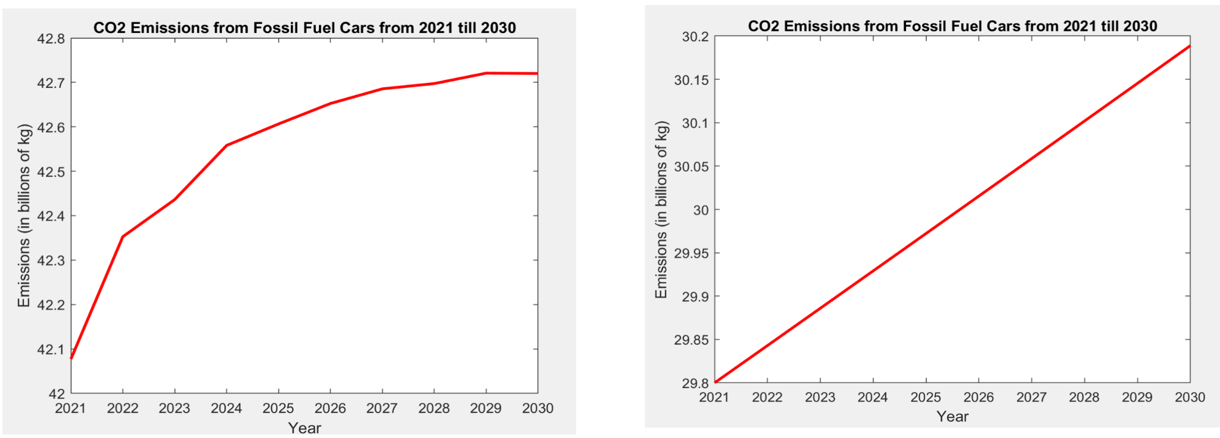

Figure 3.8: This figure on the left represents a direct conversion from energy usage to CO_2 emission of fossil-fueled cars, while the figure on the right is adjusted with a real-time value from 2021 while also keeping the same approximated trend (due to linear regression) as the left figure.

3.3. Industry sector

The industry sector is the largest energy consumer in the Netherlands, with its energy consumption divided into various categories such as petroleum products, electricity, natural gas, and the use of fossil fuels. Among these, the use of natural gas is particularly crucial when modeling future energy demand. Natural gas currently accounts for slightly over 40% of the industry sector's final energy consumption. Addressing the use of natural gas is important not only because it can be replaced by alternative gases like biogas and hydrogen, but also due to the heavy reliance on natural gas imports from Russia. Considering recent geopolitical events, such as the conflict between Ukraine and Russia, which has led to a surge in gas and energy prices, it is essential for the Netherlands and the European Union as a whole to develop new strategies and ideas to achieve complete independence from Russian natural gas. While avoiding deep political discussions, it is in the best interest of the Netherlands and the EU to prioritize initiatives that promote energy security and reduce reliance on external gas sources.

Natural Gas

The model for the Netherlands in 2030 takes into account a broader study focused on natural gas and energy independence for all of Europe. This study, conducted by Enerdata, highlights the potential for decreasing energy demand by utilizing heat pumps and implementing sufficiency measures [23]. According to the study's projections, the industry sector in Europe is expected to have a natural gas demand of 39.04 billion cubic meters (bcm) in 2030.
To convert the volume of natural gas into energy, the caloric value of natural gas in Groningen, which is 35.17 megajoules per cubic meter (MJ/m^3), is used. This conversion yields a final consumption of natural gas in terms of energy equal to 1373.04 petajoules (PJ). Comparatively, the energy demand from natural gas in 2021 was 3289.93 PJ [26].
By considering these figures and the projected decrease in natural gas demand, it becomes evident that significant progress can be made towards reducing reliance on natural gas and enhancing energy independence in the industry sector. The decrease in natural gas energy demand by 58.3% does not consider a significant utilization of hydrogen, or it only accounts for a minimal contribution. This is an aspect where the Netherlands can separate itself from the rest of Europe and the world. This is further discussed in 5.1. Looking at the data of the international energy agency for the Netherlands [38], it can be observed that the energy demand for natural gas is 228931 TJ in 2020. If the Netherlands can follow the model for Enerdata for all of Europe, it means that the natural gas demand for the industry sector will be 95.46 PJ. Using the caloric value again for natural gas of 51.72 MJ/kg, it is found that the demand of natural gas will be 1.85 billion kg.

Electricity demand

The electricity demand in the industry sector is another significant component of its final consumption. In 2021, the electricity demand was reported to be 144.2 PJ [67], representing a combination of various electricity sources, this was done by the simulation group [72]. This accounts for approximately 25.7% of the total demand in 2021. With the increasing electrification of industrial processes, it is expected that the electricity demand will continue to rise. Projections indicate a 34.7% increase in electricity demand for the industry sector by 2030 compared to 2021 [34]. These projections, based on global data, are used to model the electricity demand for the Netherlands. Consequently, it can be anticipated that the electricity demand will reach 194.2 PJ by 2030.

Final consumption

By combining the estimated values for electricity and natural gas, the calculation below can be executed for the final energy consumption for the industry sector. Assuming that the other variables remain unchanged since 2020, the calculation is goes follows:

$$560.477\,\text{PJ (demand in 2020)} - 133.466773\,\text{PJ (saved from reduced natural gas usage)} \\ +50\,\text{PJ (added due to electrification)} = 477.01\,\text{PJ}$$

Consequently, it can be inferred that the industry sector is expected to reduce its consumption by approximately 83 PJ.

4 Supply

4.1. Solar

4.1.1. Design Process and Parameter Justification

1. Solar energy modeling

Solar energy plays a crucial role in the Netherlands' energy transition. Accurate modeling of solar energy is essential for effective planning and calculating energy output. This enables decision-makers to make informed judgments [52]. The foundation for the solar energy modeling platform has already been established, utilizing the PV code from the illuminator kit [60]. This code serves as a valuable reference, providing essential guidelines for determining various parameters. The solar energy model incorporates several parameters to accurately simulate and analyze the generation of solar power. These parameters include:

1. Total surface area
2. Tilt angle
3. Efficiency of a solar panel
4. Installed capacity

The aforementioned parameters are then handed over to the simulation group [72], where utilization is done alongside irradiance data that has been profiled to a time interval, typically in 15-minute increments. This data serves as a crucial input for the simulation process, allowing the group to accurately model and analyze the performance of the solar energy system.

2. Parameter extraction guidelines

- **Total surface area**: In 2020 it was registered that 9 km^2 of land area was covered with solarparks [41]. From 2015 onwards big scale plans were made and executed into building solar parks across the country leading to a substantial rise in solar parks in a short period of time [45]. However, in recent times, the Netherlands saw a 32 percent decrease in the building of solar parks. The economic outlook for solar power projects is dismal due to the considerable increases in the expenses of labor and materials. At first glance, this may seem strange considering that electricity prices have reached record highs in recent months. However, large-scale solar power projects rely on expected electricity prices over the next 15 to 20 years, rather than current prices. Therefore, based on the current costs and expected electricity prices, the profitability of many solar power projects is not sufficiently guaranteed [65] [1].

  The graph below shows the number of PV projects and their quarterly trend as reported by CertiQ. The net increase of registered capacity has been declining steadily every quarter since the start of 2021 [27].

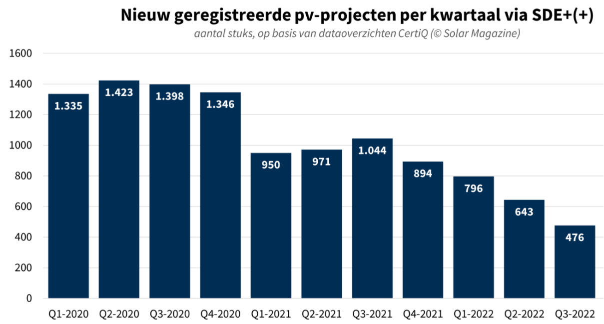

Figure 4.1: The graph illustrates a decline in the number of newly registered PV projects per quarter of a year.

Therefore, it can be confidently stated that since 2020, there has been a gradual decline in the addition of surface area when it comes to solar parks.

- **The ideal tilt angle** is the angle at which a solar panel should be installed in order to generate the greatest amount of energy. The panel receives the most direct sunlight at this angle throughout the day, which increases solar energy production. Based on a number of variables, including geographic location, time of year, and the particular use of the solar panel system, the appropriate tilt angle is established.

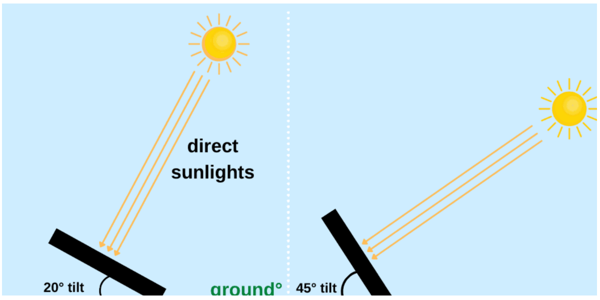

Figure 4.2: The tilt of solar panels is adjusted according to the position of the sun [46]

- **The efficiency of a solar cell** refers to the cell's capacity to transform solar energy into usable electrical energy. It is a crucial factor since it affects how well the solar cell can convert solar energy into electricity [62].
- **The installed capacity** solar cells refers to the overall power capacity of solar panels that are operational in a certain place. It reflects the maximum quantity of power that solar cells can create under ideal conditions. It is an essential statistic of a solar power system.

Solar panels on rooftops

A study done by Deloitte discusses a growth rate of 40% per year observed between 2014 and 2017 [20]. However, it is unrealistic to expect a direct translation of this trend into actual energy growth. There are several reasons why achieving a growth rate of 62 PJ in one year, as mentioned in the study, is not feasible. Even if a significant number of people were to adopt solar panels simultaneously, the process of building and installing panels to meet such energy growth would take longer than a year. Additionally, there are existing challenges related to implementing solar panels on rooftops. One specific change expected in the Netherlands is the adjustment of netting arrangements. Netting refers to the situation where excess energy generated by solar panels is sent back to the grid. Currently, individuals receive compensation for the surplus energy delivered to the grid. However, starting in 2025, the compensation for energy sent back to the grid will be reduced. This modification in netting arrangements may impact the incentive for people to invest in photovoltaic (PV) panels. Considering these factors, it is crucial to approach predictions of solar panel adoption and energy growth on rooftops with caution, taking into account the complexities and challenges associated with implementation and policy changes. The adjustment in netting arrangements may create a disincentive for individuals to invest in solar panels.

Additionally, the storage of energy generated by solar panels remains a significant challenge, with batteries being the primary storage method, albeit an expensive one. Considering these factors, relying solely on the trend of growth in PV panels on rooftops may not be the most reliable approach for modeling future growth. It is important to recognize the need for further development in storage technologies and consider the potential impacts of policy changes. A more comprehensive and realistic model to achieve global carbon neutrality by 2050 is outlined in a report by the International Energy Agency (IEA) [37]. This roadmap includes a target of installing solar panels on 25 million rooftops in the residential sector by 2030, with a projected growth to 100 million rooftops. This represents a more comprehensive and feasible approach specifically focused on households in the residential sector. The projected increase in rooftop area by 2030 is four times higher than that of 2018. This would result in an expansion from 35.7 km^2 [3] in 2018 to 142.8 km^2 in 2030 for the Netherlands. Considering the available space of 892 km^2, this estimate appears highly feasible.

4.1.2. Results and findings

- As has been discussed before, since 2020 there has been a gradual decline in the addition of **surface area**. Based on this fact a modeling opportunity is there to approximate the total area covered by solar parks in the Netherlands. Figure 4.2 has been implemented in MATLAB and extrapolation is applied to a regularly declining trend to determine the upcoming PV projects. This execution can be seen in figure 4.3 in which can be observed that the red dotted line is drawn up until slightly beyond 2023 Q2.

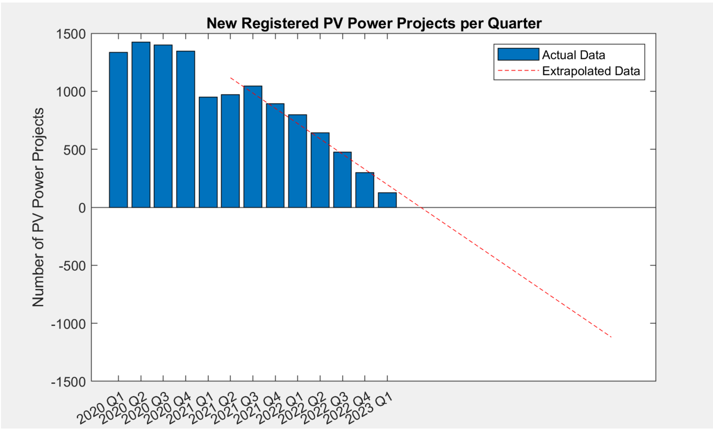

Figure 4.3: The figure shows a decline in PV projects per quarter, with extrapolation applied starting from the period 2021 Q3

Since it is known that in 2020 the total area covered by solar parks in the Netherlands was 9 km^2, an addition has been done starting from 2021 till the red dotted line crosses the X-axis. The solar parks added since 2021 equals 6276. Additionally, it is known that in 2022 the amount of solar panels for a field equals 2048, as can be seen in figure 4.4.

Since there is saturation at the end it is assumed that in 2030 there will be approximately the same amount of solar panels for a field. Moreover it is known that an average solar cell in the Netherlands has a surface of 1.6 m^2 [69]. Ultimately the total area covered by solar parks in 2030 is calculated in the following manner:

$$\text{Total\_surfacecoveredin2030} = \text{addition of pv projects} \times \text{solar panels/field} \times \text{surface area of 1 solar cell} \quad (4.1)$$

This equals 33.88308 km^2.

Finally the total area covered by solar cells in the Netherlands in 2030 equals the area covered by solar parks added to the area covered by the aforementioned solar panels on roofs:

$$\text{total\_area} = \text{area covered by solar parks} + \text{area covered by solar panels on roofs} \quad (4.2)$$

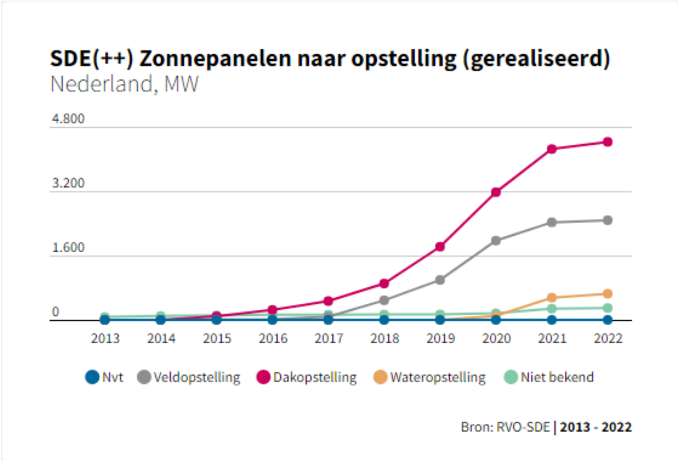

Figure 4.4: The figure shows a saturating (gray)trend in 2022 regarding the solar panels implemented per field or park in the Netherlands[58]

Hence;

33.88308 km^2 + 142.8 km^2 = 176.68308 km^2.

- **The ideal angles** for solar panel orientation in the Netherlands were determined using a weighted average approach. The weights used in the calculation were derived from a top 20 list of solar park locations in the country [63]. The ideal angles for each location were considered based on factors such as solar energy potential and sunlight exposure. The following ideal angles were included in the calculation [33]:

  – East: 13 degrees
  – Southeast: 25 degrees
  – South: 35 degrees
  – Southwest: 25 degrees
  – North: 30 degrees
  – West: 13 degrees

  These angles represent the optimal orientations for solar panels in each direction. The weights associated with each angle were derived from the solar park locations on the top 20 list based on where particular solar parks are located.

  The weighted average was then calculated using the formula:

$$\text{Adjusted Average} = \frac{2 \times \text{East} + \text{Southeast} + 5 \times \text{South} + 2 \times \text{Southwest} + 5 \times \text{North} + 5 \times \text{West}}{2 + 1 + 5 + 2 + 5 + 5}$$

  This gives an optimal solar panel orientation throughout the Netherlands using this weighted average technique. Hence, this leads to an ideal tilt angle of 24.55 degrees to maximize energy generation through solar power.

- Solar panels might attain an astounding **efficiency rate** of 30 percent by 2030. Increasing efficiency is critical to attaining the lofty objectives set by climate agreements. More sustainable energy may be created by optimizing energy output per unit area, lowering dependency on fossil fuels [55]. However, one should only take into account the solar panels that have been placed across the country in the years before 2030, as these solar panels will have a standard efficiency of around 18 percent. It is a fact that solar efficiency has a decay of 5 percent each year [22]. That would lead to a loss of 45 percent in 9 years. Fortunately, this loss is compensated with innovation and replacement. With compensation and decay in mind, the average efficiency leading up to 2030 yields 20 percent.

- The Netherlands Environmental Assessment Agency (PBL) anticipates that the country's **installed PV capacity** will nearly have a significant increase leading up to a total capacity of nearly 27 GW

[5]. To support these projections, an equation is provided to calculate the power density of a solar panel. Given a panel yield of 250 Wp [32] and panel dimensions of 1.65 m $\times$ 1 m (1.65 m^2), the power density is calculated as 151.52 Wp/m^2 on a yearly basis. Multiplying this power density by the surface area of 176.68308 km^2, the result is approximately 26.77 GW. This calculation supports the expected installed capacity of 27 GW, as it closely aligns with the projected figure. In the context of fulfilling the climate accord targets, the importance of having improved efficiency and capacity in solar energy systems becomes clear. The Netherlands can make significant progress toward meeting its renewable energy objectives. To finalize, by passing on all the aforementioned parameters to the simulation group the obtained value for solar energy generation is equal to 25958.61168 GWh [72].

4.2. Wind

The Netherlands is undergoing a remarkable energy transition, with a strong focus on wind energy. This model explores the growth, and impact of wind energy in the country. Recognizing the need to reduce greenhouse gas emissions and embrace renewables, the Netherlands has set ambitious targets and implemented supportive policies. Wind power has emerged as a key solution, with significant investments in onshore and offshore wind farms. This thesis examines the progress made and the strategies employed to integrate wind energy effectively. By studying the Dutch wind energy transition, we gain valuable insights for sustainable energy transitions worldwide.

The way the wind energy for the Netherlands is projected within this model, is to look at goals set by the government. With these goals, it is then investigated what the specifications are for wind turbines in the Netherlands. These parameters can then be used in the wind model of what is already created by the illuminator team [60]. Another important distinction that has to be made, is the difference between onshore and offshore wind energy.

4.2.1. Design Process and Onshore wind

Data for onshore wind turbines can be obtained from various sources such as CBS [17]. By utilizing the information on the total arranged rotor area and the number of wind turbines in the Netherlands in 2020, the radius and subsequently the diameter of the average wind turbine can be calculated using the formula for the area of a circle: $r = \sqrt{\frac{\text{Area}}{\pi}}$. This calculation yields an average diameter of 86 meters. Similarly, the average rated power of a wind turbine is determined to be 2.2 MW. The next parameters to be determined are the cut-in and cut-out speeds of most wind turbines.
The cut-in speed refers to the point where wind speeds are initially low, and the force from the wind is insufficient to initiate the rotation of the turbine blades. As the wind speed rises, the turbine blades gradually gain momentum and start spinning, thereby generating electrical power. This critical speed at which the turbine begins to rotate and produce power is commonly referred to as the cut-in speed. Typically, for onshore wind turbines, a more realistic value for the cut-in speed is around 3 meters per second.
As the wind speed surpasses the cut-in speed, the electrical power output of the turbine increases rapidly, as depicted in the graph. However, at a certain point, usually ranging from 10 to 15 meters per second, the power output reaches the maximum capacity of the electrical generator. This maximum output capability is referred to as the rated power output (in this case 2.2 MW), and the wind speed at which it is attained is known as the rated output wind speed. When wind speeds exceed this threshold, the turbine's design incorporates mechanisms to restrict the power output to this maximum level, preventing any further increase. The specific methods employed for this purpose may vary depending on the turbine design, but with larger turbines, it is commonly achieved by adjusting the angles of the turbine blades to maintain a consistent power output.
The cutout speed refers to the wind speed at which the forces exerted on the turbine structure become too high, posing a risk of damage to the rotor. To prevent any potential harm, a braking system is implemented to bring the rotor to a complete stop. This speed threshold is known as the cutout speed and is typically set at approximately 25 meters per second. By activating the braking system,

the turbine is effectively shut down, ensuring the safety and integrity of the rotor and the overall turbine structure. Figure 4.5 shows the power output of a wind turbine at different wind speeds. It highlights the key points, including the cut-in speed where the turbine starts generating power, the rated output wind speed where it reaches maximum power, and the cut-out speed where the turbine is stopped to prevent damage.

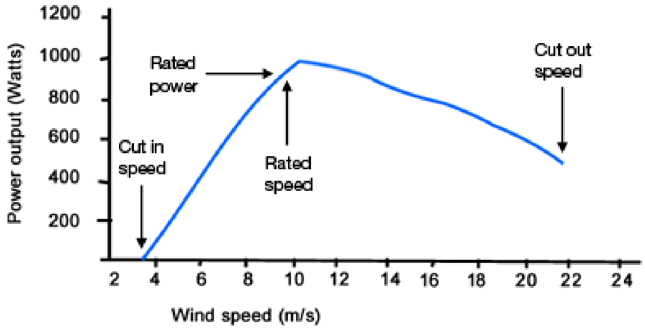

Figure 4.5: Wind generation based on wind speeds [11]

To validate the cut-in and cut-out speeds of an onshore wind turbine, the Alstom ECO 86 turbine is used as a practical example [71]. Additionally, it has been determined that the maximum installed capacity for wind turbines in the Netherlands in 2030 is estimated to be around 7 GW, reaching a saturation point [39].
In order to analyze wind speeds, data from a specific location in Delft is taken into consideration. The wind speeds are simulated every 15 minutes at coordinates with latitude 51.8782963 and longitude 4.6172641 for the year 2019, as provided by [49]. Assuming that the wind speeds will remain similar in 2030, all of this data can be used to run the code and simulate the total energy generation from onshore wind in the Netherlands. According to the simulation carried out by the simulation team, utilizing the parameters outlined in this section, the Netherlands generated a total of 22.4 TWh of energy from onshore wind [72].

4.2.2. Offshore Wind

For offshore wind, similar techniques are applied as mentioned in section 4.2.1. By utilizing data on installed wind turbines [43] and data on installed capacity [18], the average rated power of an offshore wind turbine is calculated to be 5.32 MW. The total capacity for offshore wind will reach 21 GW in 2030 [2]. It is important to note that wind turbine technology is continuously improving, with the development of larger turbines such as 12-15 MW [70].
Considering an average rated power of 6 MW for offshore wind turbines in 2030, a wind turbine model such as the Siemens SWT-6.0-154 is taken as a reference [71]. This provides the required information, including a cut-in speed of 4 m/s, a cut-out speed of 25 m/s, and a rotor diameter of 154 meters. By applying the same methodology as for onshore wind, the wind speed for offshore wind energy in the Netherlands can be determined. The coordinates used for offshore wind projects are an average location where these projects are expected to be installed. A latitude of 52.19 and longitude of 4.14.
Utilizing this data, the wind speed analysis is conducted, assuming that the wind speed in 2030 will remain consistent with the wind speed profile (every 15 minutes) in 2019. Based on this analysis, it is estimated that offshore wind energy will generate approximately 60.9 TWh in 2030. The final value mentioned is obtained by providing all the described parameters to the simulation group [72], in which the code was run using these various inputs to calculate the energy generation.

4.2.3. Findings

The results show that wind energy generates a total of 83.3 TWh in 2030. This is a significant portion of the ambitious goals set forth in the climate agreement in the 55% package which is 120 TWh from renewable sources.

5 Storage

5.1. Hydrogen

More than half a century ago, significant natural gas deposits were found in the Netherlands, leading to the establishment of an advanced and expansive gas distribution network. Presently, another groundbreaking shift is occurring as carbon-neutral hydrogen is being introduced, marking a second revolution in the gas industry. The utilization of hydrogen extends beyond its role as feedstock or fuel and serves as an energy carrier that can address systemic challenges by facilitating greater integration of renewable energy into the energy system. While there are obstacles to overcome, prioritizing the advancement of hydrogen development is crucial for ensuring the success of the energy transition. There is a pressing urgency to significantly diminish the worldwide carbon footprint in order to prevent the catastrophic effects of climate change. To achieve this, international collaboration and technological advancements play vital roles in enabling the successful and extensive decarbonization of our societies. Among various technologies, one stands out as essential for addressing persistent challenges: clean hydrogen, encompassing its production, distribution, storage, utilization, and trade.

Methodology and calculation

In this model, only green hydrogen produced through electrolyzers is considered. The climate agreement of the Netherlands has established a target of 3-4 GW specifically for the capacity of electrolyzers by 2030 [57]. By considering this target and certain parameters, it is possible to calculate the potential hydrogen production in 2030. One important parameter is the efficiency of the installed electrolyzers. Currently, there are electrolyzers under development that have the potential to achieve an efficiency of up to 80% [35]. Taking a conservative approach, let's assume that the installed electrolyzers in the future will have an efficiency similar to that of AEM electrolyzers, which is approximately 62.5% [35][21]. The next variable that needs to be determined is the full load hours the electrolyzers will operate on, on a yearly basis. Based on the model's focus on green hydrogen production with a direct connection to wind parks, it is advised by the SDE++ (Stimulation of Sustainable Energy Production) that electrolyzers operating under these conditions should have approximately 4000 full load hours per year [54].

In order to determine the annual production of hydrogen by the electrolyzers, it is essential to consider the energy density of hydrogen. The energy density of hydrogen is approximately 33.33 kWh per kilogram, which is equivalent to 120 MJ/kg [31]. Using the provided parameters, we can now determine the quantity of hydrogen that can be generated in 2030.

Given that the calculation is relatively straightforward and not excessively complex, there is no need to include it in the appendix. To determine the energy generated through the process of hydrogen production utilizing an electrolyzer of 3.5 gigawatts (GW) capacity, operating for 4000 hours annually, and achieving an efficiency of 62.5%, the following procedure can be employed:

1. Calculate the energy output in gigajoules (GJ):

$$\text{Energy output} = \text{Power capacity} \times \text{Efficiency} \times \text{Operation hours}$$
$$\text{Energy output} = 3.5\,\text{GW} \times 0.625 \times 4000\,\text{hours}$$
$$\text{Energy output} = 8,750\,\text{GWh}$$

$$\text{Energy output} = 8,750\,\text{GWh}$$
$$\text{Energy output } = 31.5\,\text{PJ} = 3.15 \times 10^{10}\,\text{MJ}$$

To determine the amount of hydrogen required to produce this energy, we need to consider the energy content of hydrogen. As previously stated, the energy content of hydrogen is approximately 120 megajoules (MJ) per kilogram (kg).

$$\text{Amount of hydrogen (in kg)} = \frac{\text{Energy output (in PJ)}}{\text{Energy content of hydrogen (in MJ/kg)}}$$
$$\text{Amount of hydrogen (in kg)} = \frac{31.5\,\text{PJ}}{120\,\text{MJ/kg}}$$
$$\text{Amount of hydrogen (in kg)} = \frac{3.15 \times 10^{10}\,\text{MJ}}{120\,\text{MJ/kg}}$$
$$\text{Amount of hydrogen (in kg)} = 262.5 \times 10^{6}\,\text{kg}$$

Hence, employing a 3.5 GW electrolyzer operating at an efficiency of 62.5% for 4000 hours annually would yield an estimated quantity of around 262.5 million kilograms of hydrogen.

Discussion of the findings

The indication is that there is a viable option to direct all of the produced hydrogen toward the industry sector, effectively replacing a significant portion of natural gas. With the natural gas demand projected to be around 95 petajoules, incorporating hydrogen could potentially reduce this demand to approximately 65 PJ. Consequently, in 2030, there would be no immediate need to convert hydrogen back into electricity, avoiding the efficiency loss associated with such conversion. Utilizing hydrogen as a substitute for natural gas would be highly beneficial for the country. As mentioned in the introduction of this section, the Netherlands has the advantage of an established distribution network, allowing for the effective utilization of hydrogen. This makes it quite feasible to produce the projected amount of hydrogen and have it actively employed before the end of 2030.

5.2. Battery

The increased deployment of solar energy in the Netherlands has put pressure on the Dutch electrical infrastructure, especially during bright days when the solar power output is at its greatest. The grid's smooth operation is jeopardized by this congestion. However, the usage of batteries provides an excellent answer to this problem. Batteries provide a dependable and effective way to balance the supply and demand for power by exploiting their capacity to store surplus electricity during periods of overproduction and discharge it during periods of underproduction [4].

Methodology and calculation

The analysis of supply and demand dynamics throughout time is offered as a concept for evaluating the energy storage capacity of batteries. This idea entails graphing the supply and demand curves with time represented on the x-axis and power on the y-axis. To evaluate possible surplus power that may be stored in batteries, the times when the supply curve is higher than the demand curve are noted.

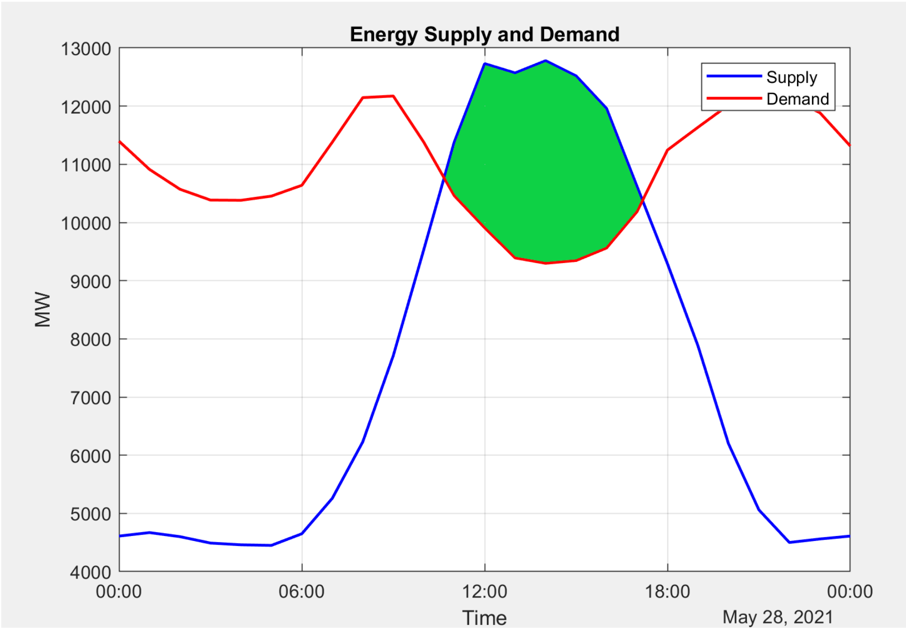

Figure 5.1: A graph, plotted on May 21, 2021, captures the supply and demand curves, showcasing the significant solar power generation on that day. The graph illustrates the relationship between supply and demand, with a green integral representing the total energy available for total storage.

Figure 5.1 highlights a day in May 2021 to which the supply curve of sustainable sources and demand curve is plotted. It can be observed that an integral is taken when the supply curve is above the demand curve [48]. This green area is then suited for storage and happens to be equal to 80886.51 MWh.

Although it can be difficult to precisely estimate the actual amount or percentage of excess energy available for storage using this approach, it offers important insights into the dynamics of energy supply and demand. The significance of taking into account the temporal changes in energy production and consumption while building and improving battery storage systems is stressed by including this idea in the thesis.

A more straightforward technique is included in the research to complement this analysis. An estimated 10 GW [47] installed battery storage capacity forecast for 2030 combined with a 2-hour storage period [6], obtained from an average large battery in the Netherlands having a rating of 24 MW/48 MWh.This eventually yields a 20 GWh overall energy storage capacity. This technique offers a realistic assessment of the storage capacity and acts as a benchmark for assessing the possible advantages and uses of battery storage technology.

Discussion on findings

This method, which is based on graphing the supply and demand curves, offers insightful information about the energy dynamics and indicates times when there is excess energy that might be stored. In contrast, a more realistic method is used to complement this estimate, taking into account the anticipated installed battery storage capacity of 10 GW by 2030, with a storage lifetime of 2 hours. This estimate yields a 20 GWh total energy storage capacity.

6 Import and Export

The prediction that the Netherlands would depend on power imports after 2025 emphasizes the need of estimating energy import and export in the future [28]. This prediction emphasizes how important it is to model energy imports and exports in order to determine the possible effects of relying on outside sources.

6.1. Modeling import/export in scenarios

Modeling energy import/export is complex due to regulations and economic conditions. Higher GDP can drive energy demand, increasing imports, but it can also boost industrial production and energy-intensive products, leading to higher energy exports. Four GDP-based scenarios are chosen for future modeling. To ensure export accuracy, overall supply and demand are considered. If demand exceeds supply, exports align with imports, while energy surplus is exported. Export growth follows import patterns. The four scenarios are:

- Scenario 1 assumes a follow-up of the historical trend including its crisis eras such as the economic crisis in 2008 or the COVID-19 period [16].
- Scenario 2 assumes a follow-up of the historical trend excluding its crisis eras.
- Scenario 3 entails a model established by Rabobank [25]. This model outlines the elements that lead to the Netherlands' long-term economic prosperity. It examines the contributions of total factor productivity (TFP), capital, and labor to GDP growth. The following connections can be found between it and the import and export of energy:

  1. **Labor**: The model examines labor's impact on economic growth, specifically average work hours per employee. Aging and declining labor force participation can affect energy imports and exports. This includes the availability of skilled workers in the energy industry and the demand for energy-related services.
  2. **Capital**: The model focuses on capital's role in GDP growth, specifically capital deepening (increasing capital per hour of labor). Investment levels influence the expected increase in capital. In terms of energy import and export, capital deepening involves investments in renewable energy.
  3. **Total Factor Productivity** (TFP): Represents the efficiency and technological progress in utilizing both labor and capital to create value-added. The report emphasizes the importance of investing in knowledge and innovation to stimulate TFP growth. This aligns with the need for advancements in energy technologies, such as energy storage systems. By improving TFP in the energy sector, countries can enhance their competitiveness in energy import and export markets.

  By incorporating these factors a well-established economic growth rate is extracted.

- Scenario 4 is based on the assumption that the public would support an expedited transition to renewable energy sources due to ambitious government goals, new technology, and breakthroughs. The Netherlands might become a net exporter of energy if energy imports are significantly reduced, according to this analysis [7].

6.2. Discussion of results

- For scenario 1 the data of GDP growth from 2005 till 2021 has been taken into account [16], then an average growth is calculated in the following manner:

$$\text{average growth GDP} = \frac{\text{total growth}}{\text{number of years}} \tag{6.1}$$

  This yields a growth of 1.475 percent.
- For scenario 2 the same approach has been used but now the crisis periods 2008-2009 and 2020-2021 have been excluded. The obtained growth is then equal to 2.2286 percent.
- Scenario 3 provides a GDP growth of 1 percent in 2030. See the figure below:

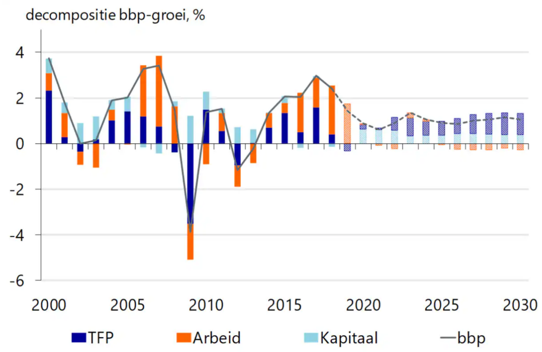

Figure 6.1: This figure shows the effect of anticipated labor (orange), capital (light blue), and TFP (dark blue) on the annual GDP rate leading up to 1 percent in 2030 for scenario 3 [25].

- For scenario 4 by 2050, the Dutch economy hopes to have an economy focussed on renewable energy. A preliminary goal of a 55 percent decrease by 2030 has been established. In addition, the Netherlands is among the top five most competitive economies. The sustained growth potential of 2 percent of the gross domestic product (GDP) is influenced by a positive business climate nationwide [7].

These 4 scenarios form a boundary region on which the import and export of energy depend. Based on the sound analysis of Rabobank and the likely shift towards an environment that supports renewable energy sources [52]. It can be concluded that the economic growth rate is in between scenarios 3 and 4, which equals 1.5 percent and since we are modeling from 2023 onwards this will lead to an accumulative addition of 1.5 percent for 7 years until 2030 is reached, hence an additive percentage of 10.5 percent. Finally, to calculate the import and export of energy in 2030 the current energies are multiplied by a factor of 1.015:

Given:

- Current energy of import = 5033 *10^6 kWh
- Current energy of export = 6055 * 10^6 kWh

$$\text{Energy of import: energy\_of\_import} = \text{current\_energy of import} \times 1.105 \tag{6.2}$$
$$\text{Energy of export: energy\_of\_export} = \text{current\_energy of export} \times 1.105 \tag{6.3}$$

This yields in:

- 5561.465 * 10^6 kWh of energy import
- 6690.75 * 10^6 kWh of energy export

7 Validation

To assess the choices made for this project, The first thing to be looked is final consumption values, see figure 7.1. When looking at the figure, it was reasonable to only take into account buildings, industry, and transport as these account for 80% of the final consumption.

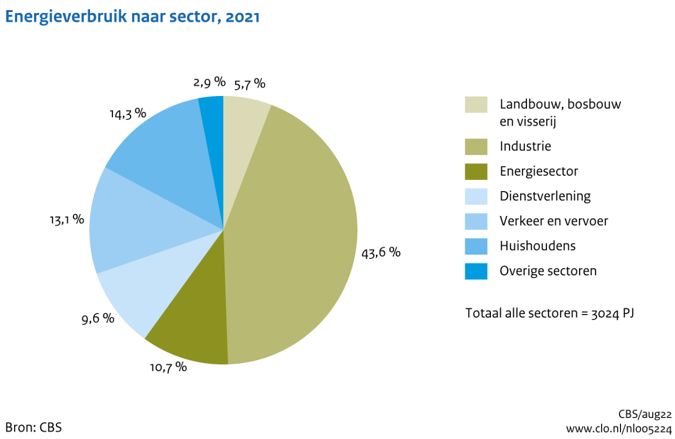

Figure 7.1: Total consumption 2021

Given that the results of our project pertain to the year 2030, explicit validation of the outcomes is extremely challenging at present. Instead, it is crucial to provide thorough justifications and reasoning behind the choices made throughout the project. These justifications are extensively discussed in the respective sections where the decisions are presented. There is a possibility of comparing our results with other energy transition models. For instance, a study discovered that implementing energy measures for heating and cooling purposes would lead to a 17% reduction in energy consumption in China's building sector [42]. If we consider both the residential and non-residential sectors, the total energy consumption would decrease from 647,715 TJ to 549,771 TJ, resulting in a 15.1% reduction. The slight deviation from our own result could be attributed to variations in building types and quantities in China compared to our study. Regarding the industry sector, our model was based on the framework established by [23]. Therefore, it can be inferred that our model aligns with their findings, providing a degree of validation.
In terms of renewables and storage, we adopted a similar approach. We examined realistic targets set by government entities and companies and utilized that information to derive relevant parameters necessary to meet those objectives. By incorporating these parameters, we aimed to ensure that our model aligned with the goals outlined by the respective entities.

8

Conclusion and Discussion

8.1. Conclusion

In our research and study, we looked at different kinds of energy demands in the Netherlands. We then found ways to make an as accurate as possible model for every sector for 2030.

Buildings

For the residential sector it was found that due to innovation in insulation, a little over 10 PJ could be saved compared to 2020. The final consumption was 373111 TJ
For the nonresidential sector, it was found with the same standards as for residential households and oversimplification for the building type that we save around 87 PJ which ends with a final consumption of 176659 TJ.

Transport

The total CO2 emissions in 2030 is calculated by summing the CO2 emissions of electric vehicles (EVs) and fossil fuel cars. CO2 emission of EVs in 2030: 1.3 billion kg CO2 emission of fossil fuel cars in 2030: 30.1889 billion kg this leads to:
Total CO2 emission in 2030 = 1.3 + 30.1889 = 31.4889 billion kg.
Regarding the total energy demand in 2030, the values provided are as follows: Energy demand in 2030 for EVs: 1202180 billion Joules Energy demand in 2030 for fossil fuels: 322957000 billion Joules for fossil fuels thus:
Total energy demand in 2030 = 1202180 billion Joules + 322957000 billion Joules = 323.2 PJ

Industry

Due to lowering the amount of natural gas used, 133 PJ is saved from 2021 till 2030. Due to innovation and electrification in the industry sector, 50 PJ will used extra for these electrical processes. Final consumption is 477 PJ.

Total demand

This implies that based on our calculations and models, the combined demand for the sectors we considered is projected to be 873 PJ by the year 2030.

Solar and wind energy

For solar generation on land, a generation of 25.958 TWh was found. For onshore wind generation, an accurate model was made that lead to a generation of 22.4 TWh. This means that generation on land was 22.4 TWh + 25.958 TWh = 48.358 TWh. For offshore wind generation, also an accurate model was made that lead to a generation of 60.9 TWh. Total wind generation in 2030 is 83.3 TWh. Total generation from renewables in 2030 is 109.3 TWh.

Storage
It was calculated that hydrogen production could be scaled up to 31.5 PJ or 262.5 million kilograms of hydrogen. It was also found that the use of hydrogen when routed to the industry sector could further reduce the natural gas demand to 63.5 PJ.
Battery storage could deliver up to 20 GWh or 72 TJ of energy in 2030.

Import and export
The calculated import for 2030 amounts to 20.01 PJ. However, since the subtraction of supply from demand results in a negative value, indicating a lack of energy surplus, we will not be exporting energy as specified in trade-off requirement 1. Instead, a simplified solution based on economic factors has been proposed, with an estimated energy export of 24.08 PJ, as mentioned in chapter 6.

8.1.1. Mandatory requirements

Requirement 1 stated that a minimum of 49 TWh must be generated from offshore wind and 35 TWh from combined sources on land. With the realistic plan of installed capacity and realistic input variables, the requirement was met. Requirement 2 stated that we should not go overboard with estimating capacity so that there would be too much generation, that it would exceed 120 TWh. Seeing as with our model, 108.4 TWh would be generated, this requirement was also met.

8.1.2. Trade off requirements

Regrettably, due to time limitations and errors in the process, a significant portion of the trade-off requirements was not fulfilled. Requirement 1 was not met at all, as there was a substantial amount of energy that still relied on traditional energy sources and could not be substituted. There was no surplus energy generated. Regarding requirement 2, it was only addressed for the transport sector and not for other sectors. However, requirement 3 was successfully implemented and produced accurate results.

8.2. Discussion

Our project has several limitations. For instance, we only considered insulation and space heating improvements in the building sector, which is the most significant and influential component in that sector. However, in order to enhance accuracy, it is necessary to incorporate additional data. This especially applies to the import and export sector in which an oversimplified approach has been taken to obtain the import and export energy in 2030, while obviously far more considerations must be taken into account. On top of that, it was quite unfortunate that there was not enough time to obtain data about how much power on average goes to battery storage specifically, which has led to another simplification. This requirement applies to all sections, as more detailed parameter extraction could greatly benefit the project. Unfortunately, due to time constraints, we simplified this aspect. Another limitation that should not be disregarded is the omission of grid congestion in our model. Considering that the increased energy generation will strain the grid, grid congestion is an important aspect of the transition that we failed to consider due to there not being enough time.

8.2.1. Recommendations

Future research should concentrate on improving the energy models by diving deeper into parameter extraction without approximating values and perhaps looking for better methods. Future research should focus on filling in any information gaps, such as those regarding the impact of consumer behavior on energy consumption or the impact of government regulations. Looking into consumer behavior and its impact on energy demand is highly recommended as this can help in load management and ensure a more balanced grid.

A

Appendix

A.1. Insulation improvement calculations

This section shows the calculations that were made by applying formula 3.1.1 for all building types that were taken into consideration.

Energy saved for an apartment

$$\text{Energy Saved (in a year)} = (U1 - U2) \times A \times \text{HDD} \times 24$$
$$\text{Facade} \Rightarrow U1 = U2 \quad \text{(no energy saved)}$$
$$\text{Ground floor} = \text{Roof} = 11.9 \times 8.3 = 98.77\,\text{m}^2$$
$$\text{Energy saved (floor)} = (0.28 - 0.2) \times 98.77 \times 1984 \times \frac{24}{1000} = 376\,\text{kWh}$$
$$\text{Energy saved (roof)} = (0.2 - 0.17) \times 98.77 \times 1984 \times \frac{24}{1000} = 141\,\text{kWh}$$
$$\text{Total save} = 376 + 141 = 517\,\text{kWh}$$
$$0.33 \times 8,063,493 \times 517 = 1,375,712,540.73\,\text{kWh}$$

Energy saved for a corner house

For a corner house, we consider the thermal envelope area of the building (verliesoppervlakte in Dutch). We calculate the average U value for facades, roof, and ground floor (as the effect of windows and front door is negligible and no data is available for their area).
We start with an average U value of 0.2, and our goal is to achieve an average of $\frac{0.2+0.2+0.17}{3} = 0.19$ W/m^{2}K.

$$\text{Energy saved} = (0.2 - 0.19) \times 230 \times 1984 \times \frac{24}{1000}$$
$$= 48\,\text{kWh}$$
$$0.13 \times 8,063,493 \times 48 = 50,316,196.32\,\text{kWh}$$

Energy saved for terraced houses

For terraced houses, we take the same approach as for corner houses. We calculate the average current U value, which is $\frac{0.2+0.2+0.29}{3} = 0.23$. Our goal is to achieve an average U value of $\frac{0.2+0.2+0.17}{3} = 0.19$ W/m^{2}K.

$$\text{Energy saved} = (0.23 - 0.19) \times 156.9 \times 1984 \times \frac{24}{1000}$$
$$= 299\,\text{kWh}$$
$$0.36 \times 8,063,493 \times 299 = 867,954,386.52\,\text{kWh}$$

Energy saved for semi-detached houses

For semi-detached houses, we calculate the average current U value, which is $\frac{0.2+0.17+0.29}{3} = 0.22$. Our goal is to achieve an average U value of $\frac{0.2+0.2+0.17}{3} = 0.19\,\text{W/m}^2\text{K}$.

$$\begin{aligned}\text{Energy saved} &= (0.22 - 0.19) \times 268.5 \times 1984 \times \frac{24}{1000} \\ &= 384\,\text{kWh} \\ 0.13 \times 8,063,493 \times 384 &= 402,529,570.56\,\text{kWh}\end{aligned}$$

Energy saved for detached houses

For detached houses, we calculate the average current U value, which is $\frac{0.2+0.2+0.29}{3} = 0.23$. Our goal is to achieve an average U value of $\frac{0.2+0.2+0.17}{3} = 0.19\,\text{W/m}^2\text{K}$.

$$\begin{aligned}\text{Energy saved} &= (0.23 - 0.19) \times 358.4 \times 1984 \times \frac{24}{1000} \\ &= 683\,\text{kWh} \\ 0.05 \times 8,063,493 \times 683 &= 275,368,285.95\,\text{kWh}\end{aligned}$$

We observe that the most significant energy savings are achieved with detached houses, which is logical since detached houses have the largest thermal envelope area and can benefit the most from improved insulation.

Total Energy Saved in the Residential Sector

The total energy saved due to improved insulation in the residential sector can be calculated by summing up the energy saved for each building type.

$$\begin{aligned}\text{Total Energy Saved} &= 137,571,2540.73\,\text{kWh} + 50,316,196.32\,\text{kWh} \\ &\quad + 867,954,386.52\,\text{kWh} + 402,529,570.56\,\text{kWh} \\ &\quad + 275,368,285.95\,\text{kWh} \\ &= 2,971,880,980\,\text{kWh} = 1.069877 \times 10^4\,\text{TJ}\end{aligned}$$

Assuming all conditions are met, we can estimate the energy used in 2030.

$$\begin{aligned}\text{Energy Used in 2030} &= 383,810\,\text{TJ} - 1.069877 \times 10^4\,\text{TJ} \\ &= 373,111\,\text{TJ}\end{aligned}$$

Energy saved for office buildings (non-residential sector)

For office buildings, the average current U value is 0.25. Although the goal of 0.19 is not a specific standard for office buildings, for simplicity and lack of data, we will consider the same nZEB (nearly Zero Energy Building) standard used for the residential sector.

$$\begin{aligned}\text{Energy saved} &= (0.25 - 0.19) \times 7240.8 \times 1984 \times \frac{24}{1000} \\ &= 20686\,\text{kWh}\end{aligned}$$

There are 1,171,554 buildings in the non-residential stock. Using the energy saved per building calculated earlier (20,686 kWh), we can determine the total energy saved over all of the Netherlands.

$$\begin{aligned}\text{Total energy saved} &= 20,686\,\text{kWh} \times 1,171,554 \\ &= 24,234,766,040\,\text{kWh} \\ &= 87245.16\,\text{Terajoules (TJ)}\end{aligned}$$

$$\text{Total energy used for non-residential buildings} = 263905\,\text{TJ} - 8.724516 \times 10^4\,\text{TJ} = 176659\,\text{TJ}$$

A.2. Codes used for modelling

Energy demand for fossil fuel cars

```
year = 1990:2019;
%fossil fuels in miljarden (10^9) kg
benzine = [3.44, 3.46, 3.59, 3.79, 3.89, 4, 4.18, 3.78, 3.92, 3.99, 3.95, 4.08, 4.14, 4.17,
    4.14, 4.1, 4.17, 4.18, 4.17, 4.17, 4.17, 4.24, 4.04, 3.94, 3.89, 3.89, 3.99, 4.13, 4.24,
    4.33];
diesel = [5.49, 5.72, 6.07, 6.14, 5.83, 5.87, 6.17, 6.21, 6.4, 6.54, 6.74, 6.81, 6.95, 7.16,
    7.33, 7.52, 7.77, 7.85, 7.91, 7.4, 7.42, 7.5, 7.27, 6.76, 6.34, 6.35, 6.27, 6.46, 6.65,
    6.54];
lpg = [0.91, 0.89, 0.87, 0.84, 0.8, 0.8, 0.79, 0.75, 0.72, 0.64, 0.56, 0.52, 0.5, 0.44, 0.44,
     0.42, 0.4, 0.34, 0.34, 0.34, 0.32, 0.29, 0.28, 0.27, 0.2, 0.18, 0.17, 0.15, 0.14, 0.13];

density_benzine = 700;
density_diesel = 830;  %in kg/m^3
density_lpg = 493;
%calculation of volume
volume_benzine = benzine/density_benzine;
volume_diesel = diesel/density_diesel;
volume_lpg = lpg/density_lpg;

%calculation of energy in J for benzine, diesel and lpg

%combustionheats
combustionheat_benzine = 33*10^9;
combustionheat_diesel = 36*10^9;   % *10^9 in J/m^3
combustionheat_lpg = 27.000*10^9;

%final energy of 3 fossil fuels
energy_benzine = volume_benzine * combustionheat_benzine;
energy_diesel = volume_diesel * combustionheat_diesel;
energy_lpg = volume_lpg * combustionheat_lpg;

demand = [energy_benzine', energy_diesel', energy_lpg'];
demandtotal = energy_benzine + energy_diesel + energy_lpg;



% plot the historical data for diesel and benzine and lpg
figure;
plot(year, demand(:,1), 'b-', 'LineWidth', 2);
hold on;
plot(year, demand(:,2), 'r-', 'LineWidth', 2);
hold on;
plot(year, demand(:,3), 'g-', 'LineWidth', 2);
title('Historical Energy Demand for Diesel and Benzine');
xlabel('Year');
ylabel('Demand (in billions of Joules)');
legend('Benzine', 'Diesel', 'LPG');

% calculate total energy demand for all three fuels
total_demand = demand(:,1) + demand(:,2) + demand(:,3);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Calculate total energy demand for all three fuels
%total_demand = demand(:, 1) + demand(:, 2) + demand(:, 3);

% Function call to 'correlation_coefficient' to obtain the correlation coefficient
% to insert influence of EV rise
weighing_factor = 0.64;

total_demand = total_demand * weighing_factor;
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% plot the historical data for all combined
figure;
plot(year, total_demand, 'k-', 'LineWidth', 2);
title('Historical Energy Demand for Diesel, Benzine, and LPG');
xlabel('Year');
ylabel('Demand (in billions of Joules)');
legend('Total Demand');



% create the ARIMA model and make predictions
model = arima(3,0,3);
fit = estimate(model, total_demand);
[prediction, ~] = forecast(fit, 10, 'Y0', total_demand);

% plot the predicted data
figure;
plot(year, total_demand, 'k-', 'LineWidth', 2);

plot(2021:2030, prediction, 'r--', 'LineWidth', 2);


title('Energy Demand Prediction');
xlabel('Year');
ylabel('Demand (in billions of Joules)');
legend('Total Demand', 'Predicted Demand');
```

Energy demand for EVs

```
evs = [117826, 138204, 196817, 270668, 381823, 515838, 539927];
average_consumption = 684000; % J/km (example value)
year = 2017:2023;
days_per_year = 365;
average_km = 11000; % on yearly basis

% Calculation of total energy usage in Joules
total_energy_usage = evs * average_consumption * average_km;

% Extract slopes based on data from 2020-2022
data_years = 2020:2022;
data_energy = interp1(year, total_energy_usage, data_years, 'linear', 'extrap');
slopes = diff(data_energy) ./ diff(data_years); % Calculate the slopes

% Prediction years
prediction_years = 2010:2030;

% Initial stage: slow growth (2010 - 2020)
initial_growth_years = 2010:2020;
initial_growth_energy = interp1(year, total_energy_usage, initial_growth_years, 'linear', '
    extrap');

% Acceleration phase: steep slope (2022 - 2036)
acceleration_years = 2022:2036;
acceleration_energy = interp1(year, total_energy_usage, acceleration_years, 'linear', 'extrap
    ');

% Apply extracted slope to the acceleration phase
acceleration_energy = acceleration_energy + (acceleration_years - 2022) * slopes(1);

% Saturation phase: plateau
saturation_years = 2037:2050;
saturation_energy = repmat(acceleration_energy(end), size(saturation_years));

% Plotting the trend
figure;
plot(year, total_energy_usage/10e9, 'o', 'MarkerSize', 8); % Original data points
hold on;
plot(initial_growth_years, initial_growth_energy/10e9, 'r--', 'LineWidth', 2);
plot(acceleration_years, acceleration_energy/10e9, 'g-', 'LineWidth', 2);
```

```
plot(saturation_years, saturation_energy/10e9, 'b:', 'LineWidth', 2);
title('Total Energy Usage of Electric Cars in the Netherlands');
xlabel('Year');
ylabel('Total Energy Usage (in billions of Joules)');
legend('Data', 'Initial Stage', 'Acceleration Phase', 'Saturation Phase', 'Location', '
    northwest');
hold off;
```

CO2 emission fossil fuels

```
fossil_fuel_cars = [318098000, 320180000, 320812000, 321733000, 322099000, 322447000,
    322696000, 322786000, 322963000, 322957000];
%energy obtained from energy demand code


years_2021_2030 = 2021:2030;


% Average carbon intensity factor in g/kWh
average_carbon_intensity_factor_g_per_kWh = 476.2;
conversion_factor = 1 / (3.6 * 10^6); % Conversion from g/kWh to g/J
average_carbon_intensity_factor_g_per_J = average_carbon_intensity_factor_g_per_kWh *
    conversion_factor;

% Calculation of total CO2 emission in kg
emission_ffs = fossil_fuel_cars * average_carbon_intensity_factor_g_per_J / 1000; % Convert
    from g to kg


% CO2 emission of ffs cars scaled
figure;
plot(years_2021_2030, emission_ffs, 'r-', 'LineWidth', 2);
title('CO2 Emissions from Fossil Fuel Cars from 2021 till 2030');
xlabel('Year');
ylabel('Emissions (in billions of kg)');
```

CO2 emission EVs

```
evs = [117826, 138204, 196817, 270668, 381823, 515838, 539927];
average_consumption = 684000; % J/km (example value)
year = 2017:2023;
days_per_year = 365;
average_km = 11000; % on a yearly basis

% Calculation of total energy usage in Joules
total_energy_usage = evs * average_consumption * average_km;

% Average carbon intensity factor in g/kWh
average_carbon_intensity_factor_g_per_kWh = 371;
conversion_factor = 1 / (3.6 * 10^6); % Conversion from g/kWh to g/J
average_carbon_intensity_factor_g_per_J = average_carbon_intensity_factor_g_per_kWh *
    conversion_factor;

% Calculation of total CO2 emission in kg
total_emission = total_energy_usage * average_carbon_intensity_factor_g_per_J / 1000; %
    Convert from g to kg

% Extract slopes based on data from 2020-2022
data_years = 2020:2022;
data_emission = interp1(year, total_emission, data_years, 'linear', 'extrap');
slopes = diff(data_emission) ./ diff(data_years); % Calculate the slopes

% Prediction years
prediction_years = 2010:2030;

% Initial stage: slow growth (2010 - 2020)
initial_growth_years = 2010:2020;
initial_growth_emission = interp1(year, total_emission, initial_growth_years, 'linear', '
    extrap');
```

```
% Acceleration phase: steep slope (2022 - 2036)
acceleration_years = 2022:2036;
acceleration_emission = interp1(year, total_emission, acceleration_years, 'linear', 'extrap')
    ;

% Apply extracted slope to the acceleration phase
acceleration_emission = acceleration_emission + (acceleration_years - 2022) * slopes(1);

% Saturation phase: plateau
saturation_years = 2037:2050;
saturation_emission = repmat(acceleration_emission(end), size(saturation_years));

%plotting the trend
figure;
plot(year, total_emission/10^9, 'o', 'MarkerSize', 8); % Original data points
hold on;
plot(initial_growth_years, initial_growth_emission/10^9, 'r--', 'LineWidth', 2);
plot(acceleration_years, acceleration_emission/10^9, 'g-', 'LineWidth', 2);
plot(saturation_years, saturation_emission/10^9, 'b:', 'LineWidth', 2);
title('Total CO2 Emission of Electric Cars in the Netherlands');
xlabel('Year');
ylabel('Total CO2 Emission (in billions of kg)');
legend('Data', 'Initial Stage', 'Acceleration Phase', 'Saturation Phase', 'Location', '
    northwest');
hold off;
```

CO2 fossil fuel linear regression

```


fossil_fuel_cars = [318098000, 320180000, 320812000, 321733000, 322099000, 322447000,
    322696000, 322786000, 322963000, 322957000];
% Energy obtained from energy demand code

years_2021_2030 = 2021:2030;

% Average carbon intensity factor in g/kWh
average_carbon_intensity_factor_g_per_kWh = 476.2;
conversion_factor = 1 / (3.6 * 10^6); % Conversion from g/kWh to g/J
average_carbon_intensity_factor_g_per_J = average_carbon_intensity_factor_g_per_kWh *
    conversion_factor;

% Determine the adjustment factor
adjustment_factor = 298000000 / fossil_fuel_cars(1);

% Adjust the fossil_fuel_cars array
fossil_fuel_cars_adjusted = fossil_fuel_cars * adjustment_factor;

% Recalculate the CO2 emissions for the adjusted data
emission_ffs_adjusted = fossil_fuel_cars_adjusted * average_carbon_intensity_factor_g_per_J /
     1000;

% Perform linear regression to estimate growth rate
x = [years_2021_2030' ones(size(years_2021_2030'))];
y = log(emission_ffs_adjusted');
coeffs = x\y;
growth_rate = exp(coeffs(1));

% Generate adjusted emissions starting from the real-time value for 2021
emission_ffs_adjusted = emission_ffs_adjusted * (29.8 / emission_ffs_adjusted(1));
emission_ffs_adjusted(1) = 29.8;

% Adjust the remaining years using the growth rate
for i = 2:numel(years_2021_2030)
    emission_ffs_adjusted(i) = emission_ffs_adjusted(i-1) * growth_rate;
end

% Plot the adjusted data
figure;
```

```
plot(years_2021_2030, emission_ffs_adjusted, 'r-', 'LineWidth', 2);
title('CO2 Emissions from Fossil Fuel Cars from 2021 till 2030');
xlabel('Year');
ylabel('Emissions (in billions of kg)');
```

Area determination of solarparks

```

% Data
new_registered_pvpower_projects_perquarter = [1335, 1423, 1398, 1346, 950, 971, 1044, 894,
    796, 643, 476, 298, 127];
quarters = {'2020 Q1', '2020 Q2', '2020 Q3', '2020 Q4', '2021 Q1', '2021 Q2', '2021 Q3', '
    2021 Q4', '2022 Q1', '2022 Q2', '2022 Q3', '2022 Q4', '2023 Q1'};

% Extrapolation
start_index = find(strcmp(quarters, '2021 Q2'));
x = start_index:length(new_registered_pvpower_projects_perquarter);
p = polyfit(x, new_registered_pvpower_projects_perquarter(start_index:end), 1);
x_extrapolated = start_index:0.1:length(new_registered_pvpower_projects_perquarter)+10;
y_extrapolated = polyval(p, x_extrapolated);

% Plot
figure;
bar(new_registered_pvpower_projects_perquarter);
hold on;
plot(x_extrapolated, y_extrapolated, 'r--');
xticks(1:length(quarters));
xticklabels(quarters);
xlabel('Quarters');
ylabel('Number of PV Power Projects');
title('New Registered PV Power Projects per Quarter');
legend('Actual Data', 'Extrapolated Data');

% Calculate cumulative addition
start_index = find(strcmp(quarters, '2021 Q1'));  %addition of 77 due to extrapolated red
    line
cumulative_addition = cumsum(new_registered_pvpower_projects_perquarter(start_index:end)) +
    77;

% Display cumulative addition
fprintf('Cumulative addition of new registered PV power projects after 2020 Q4: %d\n',
    cumulative_addition(end));

%total area covered in solarparks in 2030 be means of multipication of
%average proportion to obtain real projects being implemented multiplied by
% weighted average size of a solar park in hectare
total_surfacecoveredin2030 = 6276 * 2478 * 1.6;
%in the equation above it is multiplied by the panels per solarpark
%which again is multiplied by the average area per solarpanel

%show result of total area in 2030
fprintf('total_surfacecoveredin2030: %d\n', total_surfacecoveredin2030)
```

Ideal tilt angle determination

```

% Ideal angles NSEW
East = 13;
Southeast = 25;
South = 35;
Southwest = 25;
North = 30;
West = 13;

% Define the limit for the ideal angle
angle_limit = 50;

% Calculate the weighted sum of angles
weighted_sum = 2*East + Southeast + 5*South + 2*Southwest + 5*North + 5*West;
```

```
% Calculate the sum of weights
sum_weights = 2 + 1 + 5 + 2 + 5 + 5;

% Calculate the adjusted weighted average
adjusted_average = weighted_sum / sum_weights;

% Check if the adjusted average exceeds the angle limit
if adjusted_average > angle_limit
    adjusted_average = angle_limit;
end

% Display the adjusted weighted average
disp("Adjusted Weighted Average: " + adjusted_average + " degrees");
```

Calculating total storage on a day in may 2021 and plot of supply and demand power

```
% Energy supply and demand data
supply = [4610, 4670, 4600, 4490, 4460, 4450, 4650, 5260, 6230, 7710, 9530, 11380, 12730,
    12570, 12780, 12520, 11960, 10620, 9290, 7880, 6200, 5060, 4500, 4560, 4610];
demand = [11397, 10912, 10571, 10385, 10381, 10453, 10639, 11381, 12146, 12173, 11381, 10461,
     9909, 9391, 9299, 9346, 9561, 10186, 11245, 11636, 12018, 12155, 12141, 11887, 11314];
supply = 4.93*supply;
demand = 4.93*demand;


% Calculate the integral over the period when supply is above demand
integralValue = sum(max(0, supply - demand));

% Convert integralValue to MWh
integralMWh = integralValue;

% Display the integral value
disp(['Integral over the period when supply is above demand: ', num2str(integralMWh), ' MWh'
    ]);

% Date and time starting from 28.05.2021 00:00
startDateTime = datetime('2021-05-28 00:00', 'InputFormat', 'yyyy-MM-dd HH:mm');
time = startDateTime + hours(0:numel(supply)-1);

% Plotting the data
figure;
plot(time, supply, 'b', 'LineWidth', 1.5);
hold on;
plot(time, demand, 'r', 'LineWidth', 1.5);
hold off;

% Formatting the plot
title('Energy Supply and Demand');
xlabel('Time');
ylabel('MW');
legend('Supply', 'Demand');
grid on;
```

Economic scenarios for import and export and its calculation of growth percentages in 2030

```


%scenario 1 = following the trend including its crisis eras
% Input data
years = [2005, 2006, 2007, 2008, 2009, 2010, 2011, 2012, 2013, 2014, 2015, 2016, 2017, 2018,
    2019, 2020, 2021];
GDP_growth = [2.1, 3.5, 3.8, 2.2, -3.7, 1.3, 1.6, -1, -0.1, 1.4, 2, 2.2, 2.9, 2.4, 2, -3.9,
    4.9];

% Calculate average annual economic growth rate
numYears = numel(years);
totalGrowth = sum(GDP_growth);
```

```
averageGrowth = (totalGrowth / (numYears-1));

% Display result
disp(['Average Annual Economic Growth Rate: ' num2str(averageGrowth) '%'])

%scenario 2 = following the trend without any crisis
% Input data
years = [2005, 2006, 2007, 2008, 2010, 2011, 2012, 2013, 2014, 2015, 2016, 2017, 2018, 2019,
    2021];
GDP_growth = [2.1, 3.5, 3.8, 2.2, 1.3, 1.6, -1, -0.1, 1.4, 2, 2.2, 2.9, 2.4, 2, 4.9];

% Calculate average annual economic growth rate
numYears = numel(years);
totalGrowth = sum(GDP_growth);
averageGrowth = (totalGrowth / (numYears-1));

% Display result
disp(['Average Annual Economic Growth Rate: ' num2str(averageGrowth) '%'])

%scenario 3 and 4 are incorporated in the thesis.
```

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