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Master's Thesis

Visual Analytical System for Understanding and Simulating Germany's Overshoot Day

by

Eldhose Abraham

2129070

Supervisor:
Prof. Dr. Fabian Beck

Chair of Information Visualization

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Abstract

Ecological Overshoot Day marks when human demand on natural resources exceeds the planet's regenerative capacity. While this is widely communicated globally, interactive and country-specific analyses are scarce, limiting public awareness and evidence-based policymaking. This thesis addresses this gap by developing an Interactive visual analytics system to explore, understand, and simulate Germany's Overshoot Day. Datasets from the Global Footprint Network, Umweltbundesamt, and AG Energiebilanzen are used by the system to integrate temporal timelines, sectoral CO_2 emission breakdowns, scenario-based simulations, and forecasting tools. Built with Next.js, FastAPI, and Highcharts, the platform turns fragmented environmental data into an accessible dashboard for public engagement. A user evaluation with participants from diverse backgrounds showed usability and interpretability, with the scenario simulator and the Number of Earths needed rated as especially effective. Results highlight energy consumption and sectoral CO_2 emissions as the main drivers of Germany's ecological overshoot. The research offers an interactive dashboard that makes complex sustainability metrics accessible, enhances ecological literacy, and lays a foundation for future global comparisons and policy-relevant simulations.

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List of Abbreviations

Abbreviation	Full Form
AGEB	Arbeitsgemeinschaft Energiebilanzen: German energy balance group.
API	Application Programming Interface: Set of rules for software interaction.
ASGI	Asynchronous Server Gateway Interface: Standard for Python asynchronous web apps.
BC	Biocapacity: Nature's capacity to regenerate resources.
CSV	Comma-Separated Values: File format for tabular data.
EF	Ecological Footprint: Human demand on nature.
GET	Hypertext Transfer Protocol method for requesting data from a server.
GFN	Global Footprint Network: Research organization on sustainability.
GHA	Global Hectares: Unit of biologically productive land.
HTTP	Hypertext Transfer Protocol: Foundation of communication on the web.
JSON	JavaScript Object Notation: Lightweight data-interchange format.
OPEN API	OpenAPI Specification: Standard for describing RESTful APIs.
POST	Hypertext Transfer Protocol method for sending data to a server.
REST	Representational State Transfer: Architectural style for web services.
UI	User Interface: Point of interaction between user and system.
UBA VAR	Umweltbundesamt: German Environment Agency. Vector Autoregression.

1 Introduction

1.1 Motivation

Human activity increasingly burdens the Earth's ecosystem with resource consumption and emissions exceeding what the Earth can regenerate and absorb each year (Global Footprint Network, n.d. d). This imbalance is captured by the concept of Overshoot Day, which marks the date when its ecological resource consumption exceeds the Earth's capacity to regenerate those resources within a year. For Germany, overshoot day arrives much earlier than the global average, marking the date when the world's resources would be used up if everyone lived like an average German. This directly reflects its high per-capita consumption, highlighting an alarming ecological deficit (Global Footprint Network, n.d. a) .

Although some reliable data are available, they are often complex and fragmented, which limits their accessibility to policymakers, educators, and especially the general public, who need more awareness to delay the ecological overshoot.

In this thesis, we address this gap by introducing a visual analytic system that combines data analysis, human computer interaction, and information visualization. This approach aims to present ecological data in an interpretable and engaging format, which makes it easier for human perception and thus raises public awareness for more sustainable choices.

1.2 Problem Statement

Despite the availability of ecological data, there is no unified country specific tool that enables comprehensive exploration and simulation of the factors contributing to ecological overshoot. This represents a critical challenge in society, indicating that it has reached a stage that requires immediate attention. The data needed to analyze it is scattered across multiple sources, and no single dashboard fully consolidates this information.

Existing platforms, such as the Global Footprint Network platform or BR's CO_2-Rechner, offer valuable insights but lack detailed country-level exploration that focuses on Germany's Overshoot Day. This gap limits the ability to build a holistic understanding of what Overshoot Day is, why it occurs, what causes it, and how targeted actions might delay it. Therefore, addressing this gap is essential to foster public awareness and support data-driven decision making.

1.3 Research Question and objectives

The research aims to address the following primary question:

"How can visual analytics be used to explore and understand the drivers of Germany's Overshoot Day, and to simulate their impact on its occurrence?"

This question guides the objectives outlined in the following section and ensures that the visual analytic system directly addresses the core issues identified in the problem statement.

The research aims to design and implement a visual analytical dashboard to help users learn about Germany's historical Overshoot Day timeline, sector-wise drivers, and future projections. The major objectives are as follows:

1. Integration and preprocessing of relevant datasets from sources such as the Global Footprint Network (GFN), Umweltbundesamt (UBA), and Arbeitsgemeinschaft Energiebilanzen (AGEB)
2. Development of interactive visualizations that effectively communicate temporal and sectoral trends related to the ecological overshoot of Germany
3. Implement a simulation interface where users can adjust sliders of sector-wise reductions and observe the resulting changes in the projected German Overshoot day
4. Forecast future changes in Overshoot Day by analyzing historical data and projecting trends based on the current trajectory of Germany's Ecological Footprint.

1.4 Thesis structure

1. **Introduction:** Gives an overview of the research and explains the primary objectives of this thesis.
2. **Literature Review:** Reviews existing research on ecological overshoot, environmental metrics, and visual analytics tools related to sustainability and environmental policy support.
3. **System Design and Architecture:** Defines the design goals, technical architecture, and interaction flow of the visual analytics system.
4. **System Implementation:** Describes dataset preparation, backend and frontend development, visualization components, and deployment of the system

5. **Evaluation:** Analyzes user feedback through surveys to evaluate system usability and clarity of visualization
6. **Conclusion and Future Work:** Summarizes the research outcomes, challenges, and outlines potential future enhancements

2 | Literature review

This chapter presents key concepts, examines influence of CO_2 emissions in ecological overshoot, reviews the use of visualization techniques in environmental policy and sustainability, discusses existing tools, and finally identifies research gaps.

2.1 Key Concepts: Ecological Footprint, Biocapacity, and Overshoot Day

Ecological Footprint(EF) and Biocapacity(BC) are fundamental concepts for analyzing the relationship between human activity and environmental sustainability. The term **Ecological footprint** was coined by Wackernagel and Rees in 1994. It quantifies the biologically productive land and sea area required to meet a population's consumption needs and absorb its waste, particularly carbon dioxide. **Biocapacity**, on the other hand, refers to the ability of ecosystems to regenerate renewable resources and absorb emissions. Both measures are expressed in Global hectares (gha), a standard unit for comparison across countries and regions. (Rees & Wackernagel, 1994; Wackernagel & Rees, 1998).

Ecological overshoot occurs when a population's ecological footprint exceeds the biocapacity. The Earth Overshoot Day metric was introduced by the Global Footprint Network to communicate this concept to a broader audience in an effective manner. It marks the calendar date each year when global resource consumption surpasses Earth's capacity to regenerate those resources within the same year (Lin et al., 2025). This date is calculated using per capita ecological footprint and global per capita biocapacity data, which effectively translates sustainability metrics into a time based narrative.

These metrics were used in a detailed study conducted in Taiwan, where the concept of using the Overshoot Day was demonstrated. The results showed that while Taiwan's EF stabilized after 2012, its ecological deficit continued to rise due to declining biocapacity. Carbon related impacts dominated the footprint, accounting for approximately 61% of the total, which is above the global average. In 2018, Taiwan's Overshoot Day occurred on March 13, highlighting the extent of its ecological overshoot (Lee et al., 2021). The study highlighted the value of Overshoot Day as a policy relevant indicator for understanding national-level sustainability performances and identifying high impact sectors to assess the effectiveness of environmental policies, thereby raising public awareness.

2.2 Linking CO_2 Emissions to Ecological Overshoot

CO_2 emissions are the primary significant contributor to worldwide ecological overshoot, especially in industrialized nations like Germany. The Intergovernmental Panel on Climate Change (Intergovernmental Panel on Climate Change (IPCC), 2022) identifies energy production, transportation, industry, and agriculture as the main sources of greenhouse gas emissions. These sectors significantly influence national ecological footprints due to their high energy use and carbon intensity. Research shows that advancing sustainability in these areas requires balancing benefits and trade-offs, such as adopting renewable energy. This can lower emissions while providing economic and social benefits, but may also create challenges related to land usage and costs. The Agriculture, forestry, and other land use sector offers significant mitigation potential through forest conservation and soil carbon sequestration; however, these measures can conflict with food production and biodiversity goals. In conclusion, this study highlights that sectoral emissions are crucial not only for meeting climate targets but also for understanding and addressing ecological overshoot.

(Janković et al., 2019) employed Vector Autoregression (VAR) to investigate the dynamic relationships between primary energy consumption, economic growth, and the ecological footprint, focusing on various energy sources, including coal, oil, gas, nuclear, hydro, and renewables. Their model revealed a strong correlation between ecological footprint and energy use across all sources, with projections indicating that the global footprint would continue to rise until around 2020 before gradually declining. This is largely due to a predicted reduction in coal consumption. This decline was interpreted as a positive signal, despite overall energy demand being expected to remain high, as coal is the most carbon intensive fuel. The study emphasized that sustainable transitions require technological shifts and the rational use of natural capital within ecological limits, particularly in terms of carbon footprint across the full life cycle of fuels. These findings reinforce that fossil fuel dependency directly amplifies ecological overshoot, highlighting the central role of CO_2 emissions in shaping overshoot trajectories.

The role of CO_2 in determining overshoot trajectories has been highlighted in recent studies. (Espinosa & Koh, 2024) applied time-series models, ARIMA, and Prophet to project the ecological footprint trajectories for G20 countries over the next 30 years. Their results indicate that energy sector emissions are the primary factor driving increases in ecological footprints, with future trends expected to be influenced by population growth, economic development, technological progress, and unforeseen disruptions. The projections suggest that both developed and developing G20 countries are likely to continue consuming resources beyond their biocapacity, thereby deepening ecological deficits if strong mitigation measures are not adopted. The study highlights that large scale adoption of renewable energy, efficiency improvements, and behavioral changes are crucial pathways for reducing carbon intensity and for reshaping overshoot trajectories.

Germany's ecological footprint is primarily driven by carbon intensive energy, industry, and transportation, with two-thirds of its ecological footprint coming from carbon emissions. In 2020, Germany's per capita ecological footprint was 4.4 global hectares, 66% from carbon, while available biocapacity was only 1.5 global hectares per person (Ecological Footprint Initiative, n.d.). This gap shows that the forest area needed to absorb Germany's CO_2 emissions far exceeds the required biocapacity, causing early ecological overshoot each year. Although the COVID-19 pandemic temporarily reduced emissions in 2020, consumption rebounded quickly (Liu et al., 2021). These findings show that Germany's ecological overshoot is closely tied to its reliance on carbon intensive systems, making emission reductions essential to postponing Overshoot Day.

2.3 Visualization in Environmental Policy and Sustainability

Data visualization can play a critical role in translating complex environmental data into actionable insights, especially in communicating complex trade-offs and uncertainties to the public and decision makers. A review of visual analytics (VA) tools in sustainable lifecycle design (SLD) showed that it still faces barriers, such as limited integration of downstream lifecycle data and the difficulty of converting "big data" into "big insight even though the field has grown considerably. The study highlighted the potential of VA tools to combine automated, data driven methods with expert driven reasoning to enable interactive exploration of sustainability challenges across design, manufacturing, use, and end-of-life phases. Despite these possibilities, the study highlighted the shortage of tools integrating environmental indicators, interactivity, and long term forecasts. Advancing visualization approaches is therefore essential for lifecycle design and for strengthening environmental policy and sustainability assessment (Ramanujan et al., 2017).

A systematic review by (Metze, 2020) on visualization in environmental planning found that interactive visual tools improve transparency, support participatory decision making, and enhance policy effectiveness. The review also identified a persistent gap between visual communication and advanced data analytics. The study emphasized that visualizations have become popular in a mediatized world, where they circulate rapidly on social media, crossing language barriers, and influence public opinion more effectively than text. Their role in participatory planning and knowledge co-creation has provided insights into how societal actors perceive and reproduce environmental information. But it also raises concerns about the spread of misleading visuals. Metze concluded that researchers and policymakers should act as knowledge brokers, utilizing visualization to communicate evidence, engage with diverse audiences, and address misinformation. This approach positions visualization as a critical tool for connecting scientific expertise, societal values, and policy development in sustainability contexts.

Similarly, (Bach et al., 2024) summarized the state of the art in sustainability focused visualization tools, highlighting the need for systems that integrate multiple indicators, forecast trends, visualize uncertainty, and support interactive scenario modeling. Their workshop on Visualization for Climate Action and Sustainability showed how visualization can empower researchers, policymakers, and the public by enhancing understanding, communication, decision making, and participation across sustainability domains such as energy and climate science, the circular economy, and biodiversity. Although the field has produced iconic examples, such as climate stripes and IPCC graphics, efforts remain fragmented across disciplines, with no overarching research agenda to guide visualization for sustainability. The study stresses that consolidating visualization practices into a coherent framework is vital for realizing their full potential in environmental policy and sustainability.

2.4 Interactive Tools and Simulation in Environmental Forecasting

There are only a few existing systems that enable users to simulate how changes in technology adoption or behavior could influence sustainability indicators. Some of them are:

The Global Footprint Network (GFN) is a nonprofit organization that maintains the National Footprint and Biocapacity Accounts (NFA), which track the ecological footprint and biocapacity of more than 200 countries using standardized methodologies and UN-affiliated data (Global Footprint Network, n.d. c). GFN provides tools for individuals to assess their personal Overshoot Day and explore how changes in global parameters, such as consumption, population, and biocapacity, affect ecological debt. GFN has an open data platform and public facing tools, which are the Footprint Calculator, the Food Footprint Platform, and the Scenario Tool, as in figure 2.1 (Global Footprint Network, n.d. e). These resources help raise awareness, ensure transparency across countries, and provide consistency for both public education and high-level policy discussions. However, data are often aggregated into broad categories, and visual interactivity is basic. Sectoral drivers are not distinguished, and forecasting functions are minimal.

Several **CO_2 calculators** are available in Germany to help individuals and households estimate their carbon footprints. The **BR CO_2-Rechner**, developed by Bayerischer Rundfunk, allows users to simulate the potential impact of policy measures such as phasing out coal, replacing combustion engines with electric vehicles, or renovating buildings to

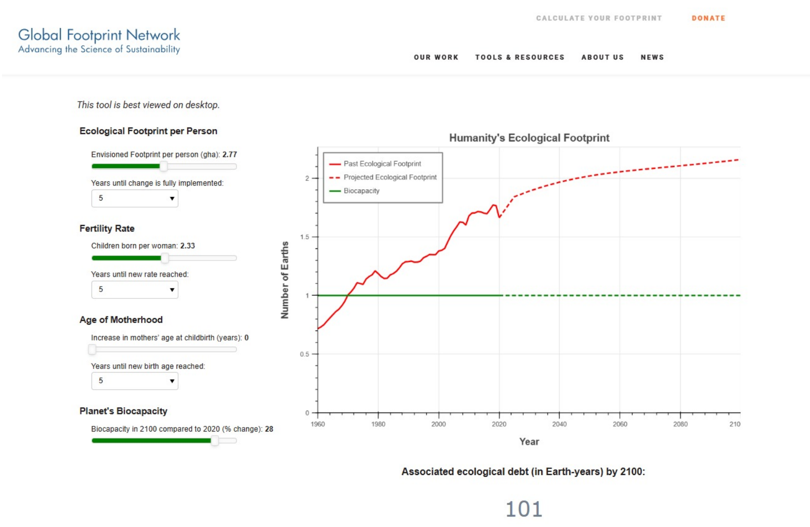

Figure 2.1: GFN Scenario Tool

improve efficiency, and situates these results within the context of Germany's climate neutrality target for 2045 as shown in figure 2.2 (Bayerischer Rundfunk (BR), n.d.).

Figure 2.2: BR CO2 Rechner

The **Quarks.de** calculator, in figure 2.3, focuses on emissions from daily transport choices, while the **MyClimate Deutschland** suite provides detailed estimates across travel, household, and lifestyle activities, including specialized calculators for flights, events, cars, and companies as shown in figure 2.4 (myclimate Deutschland, n.d.; Quarks, n.d.).

These calculators are effective in raising awareness and making climate goals relatable for German users, but they remain narrowly focused. Their scope is restricted to CO_2 emissions without linking them to ecological overshoot, and they lack a global comparison.

En-ROADS (Energy Rapid Overview and Decision Support) is a globally accessible climate simulator developed by Climate Interactive, MIT Sloan, and Ventana Systems. It enables policymakers, educators, and the public to test climate policies like carbon pricing, electrification of transportation, renewable energy expansion, and land usage changes, while instantly visualizing their long term effects on global outcomes

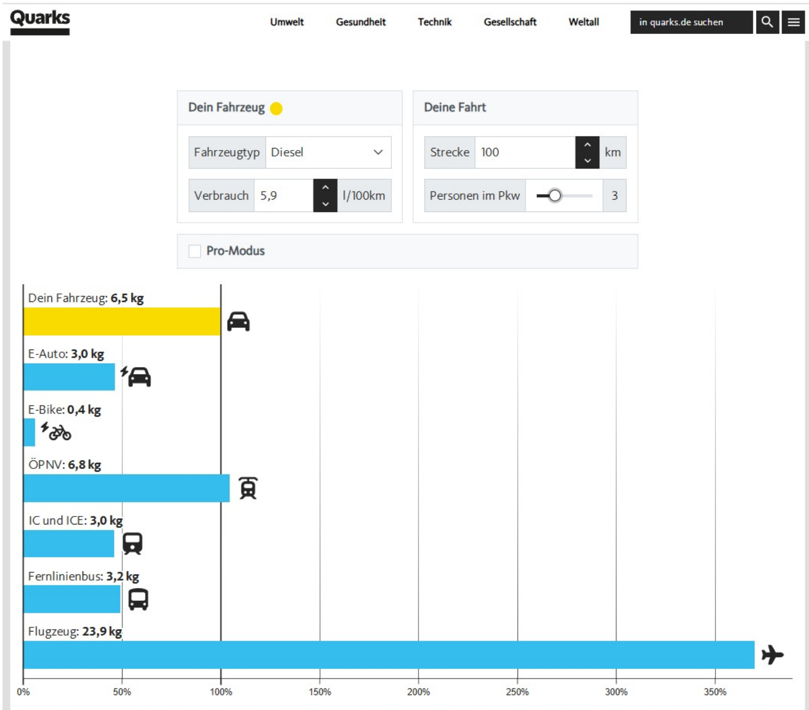

Figure 2.3: Quarks CO2Rechner

such as temperature rise, greenhouse gas emissions, air quality, and energy system transitions. The tool has been widely adopted in workshops and decision making settings worldwide for its intuitive interface and interactive scenario modeling. Its main strength is translating complex system dynamics into an engaging dashboard experience, as in figure 2.5 shows how combined policy levers shape global climate futures. However, En-ROADS is primarily designed to show global climate outcomes such as temperature rise and emissions pathways. Its interactivity is limited, and its visualization style, including sliders and dashboards, is basic. It does not cover concepts related to Overshoot Day, biocapacity, or ecological footprint.(Climate Interactive and MIT Sloan, 2025; Siegel et al., 2025)

(Liu et al., 2021) developed **AQEyes**, a visual analytics system designed to detect anomalies in air quality data through interactive filtering and time-series exploration. The system is supported by a scalable machine learning pipeline capable of handling common data challenges, such as missing values and inconsistent formats. It also integrates an LSTM-based unsupervised anomaly detection model that identifies diverse anomalous events without requiring labeled data. Its effectiveness was demonstrated through quantitative evaluation and case studies, with expert feedback confirming its utility. While the domain holds less relevance to overshoot and CO2 emissions, the architecture illustrates how interactive visualization and anomaly detection can enhance environmental data analysis, offering transferable insights for ecological footprint modeling.

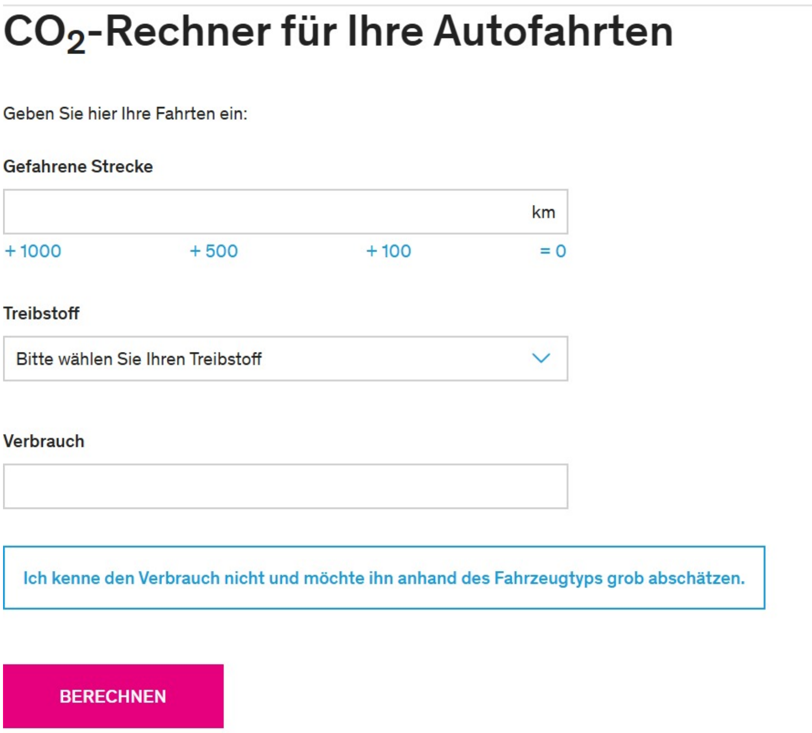

Figure 2.4: MyClimate Rechner

(Nayeem et al., 2022) developed **DCPViz**, a visual analytics system for exploring downscaled climate projections (NEX-DCP30) through coordinated views, allowing users to investigate uncertainties in forecasted data. The system was evaluated with three use cases involving climate scientists. Expert feedback confirms its potential and identifies areas for improvement. These include integration with distributed frameworks, the use of observational datasets, comparative visualizations, and interactive features. DCPViz demonstrates how coordinated and uncertainty visualizations can enhance the interpretation of complex environmental forecasts, offering relevant lessons for communicating Overshoot Day concepts through interactive, multi-view systems.

The platforms discussed above do not combine historical analysis, sectoral CO_2 emissions, interactive simulations, and forecasting of Overshoot Days into a single integrated system. This gap is especially relevant for countries with high consumption, like Germany, where decision making requires targeted and scenario based tools.

2.5 Identified Research gaps

The reviewed literature identifies several limitations that constrain the effectiveness of existing tools for Overshoot Day analysis, particularly in the German context.

Current systems provide carbon footprint estimations and sustainability dashboards, but are static and rarely support interactive exploration,

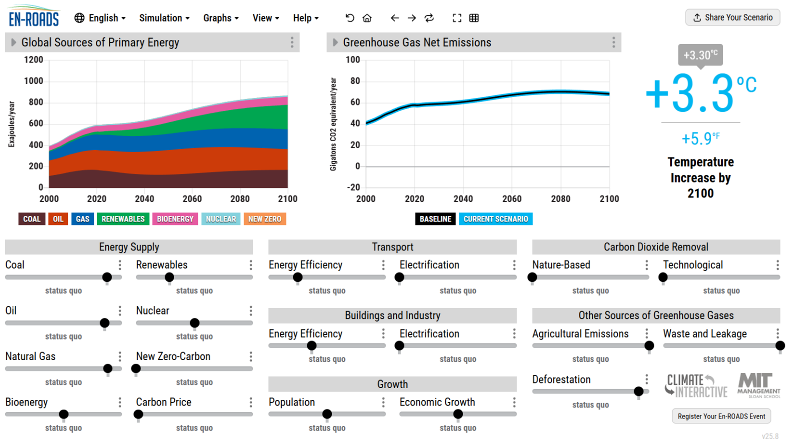

Figure 2.5: En roads

real-time feedback, or scenario modeling. Few studies incorporate user-driven simulation features that enable forecasting and experimentation with ecological footprint data.

Sectoral contributions to ecological overshoot are typically analyzed using statistical methods, but these findings are not presented through interactive visualizations. Academic studies and reports generally display sectoral emissions as static figures or textual summaries, without interactive elements. The Global Footprint Network's scenarios lack mechanisms for country specific exploration. Existing platforms do not enable users to examine how behavioral or policy changes could influence a nation's Overshoot Day.

No current system integrates visual analytics, sector wise attribution, scenario simulation, and forecasting within a unified interactive platform. Some tools address individual aspects, but none support ecological overshoot modeling for Germany with both interactive timeline visualizations and dynamic scenario forecasting.

This thesis directly addresses these gaps by developing an interactive visual analytical system tailored to Germany's ecological footprint and Overshoot Day. The system integrates open environmental data and visualization techniques. It enables users to explore historical trends, compare Germany with global averages and regional averages, visualize sector level contributions, and forecast future trajectories. This work addresses a conceptual and technical gap in sustainability visualization using a dashboard to enhance public awareness.

3 System Design and Architecture

3.1 Design Goals

Despite the increasing availability of environmental data and sustainability dashboards, chapter 2 highlights several key gaps in current tools for analyzing and communicating ecological overshoot.

This thesis proposes a visual analytics system that addresses these limitations through integrating exploration, simulation, and forecasting into a single interactive platform. The following are major design goals:

- **Enable a Global Overview with Country-Level Comparison:** An interactive world map displays Overshoot Days for all countries over a specified time period, allowing users to select a country to view its respective per capita footprint, biocapacity, and compare with global averages. This addresses the absence of globally contextualized, user-driven exploration in existing tools, serving as an intuitive entry point for deeper analysis at the country level.
- **Visualize Germany's Historical Overshoot Timeline:** A timeline with Germany's Overshoot Day, along with global and selected country trajectories. This supports comparative analysis and addresses the lack of country-specific temporal visualizations in current platforms. Users can assess how Germany's performance has evolved in relation to that of peer nations and the global average.
- **Decompose Sectoral Contributions to Overshoot:** A sector-wise view breaks down CO_2 emissions into transportation, buildings, industry, and agriculture, highlighting the connection and impact on Overshoot Day. This avoids the gap in current tools that analyze sectors statistically but fail to visualize their contributions interactively.
- **Support Real-Time Scenario Simulation:** Interactive sliders allow users to modify sector variables and immediately observe changes in Germany's projected Overshoot Day. This mitigates the absence of real-time scenario simulators for Overshoot Day at the national level. It enables users to experiment with behavioral changes in an interface that links actions to environmental outcomes.

- **Forecast Future Overshoot Days:** A forecast view that projects Germany's Overshoot Day with uncertainty, visualized based on historical data. This fills a critical gap in existing tools that provide only historical or static summaries.

3.2 System Architecture

The system is designed with a three-layer architecture consisting of the data layer, application layer, and presentation layer. This approach supports modularity and scalability. The architecture is shown in figure 3.1.

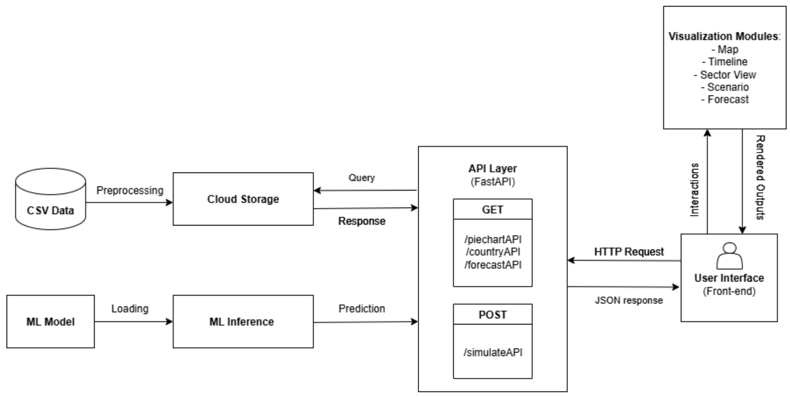

Figure 3.1: System Architecture

- **The Data Layer**: integrates datasets from external providers such as the GFN , UBA, AGEB, and NEFBA. The data from GFN is accessed via API keys, while other datasets are downloaded directly. The raw data undergoes a preprocessing and aggregation process, including cleaning, merging, and format alignment to ensure consistency. The processed datasets are then stored as CSV files in Google Cloud, which serves as the centralized repository for efficient retrieval.
- **The application layer**: was implemented with FastAPI, which acts as the middleware between stored datasets, the machine learning model, and the presentation layer. It exposes REST endpoints that support both retrieval (GET requests) and simulation (POST requests), allowing the system to provide access to preprocessed datasets, such as country level data, pie charts, and forecast results. In addition, this layer executes scenario simulations by applying user-defined inputs and returns JSON formatted responses to the frontend for dynamic visualization. All API endpoints are documented using OpenAPI, ensuring interoperability. The application layer also manages interactions with the machine learning model and generates predictions.
- **The presentation layer**: is built as a single page application using Next.js and React. Visualization modules are implemented with Highcharts, enabling users to explore interactive maps, historical timelines, sectoral decomposition, scenario simulation, and forecasting. The user interface communicates with the FastAPI backend through

HTTP requests, rendering dynamic outputs in response to JSON data. This design provides a responsive analytical environment for end users.

3.3 Interaction flow

The dashboard is a scroll-driven single-page application with a world map view at the Hero section. This component lets users explore Overshoot Days globally and serves as a starting point for further exploration. Users can scroll down to access remaining components, including the timeline view, sector wise contribution analysis, scenario simulator, and forecasting interface. When a country is selected on the world map or from the dropdown, it is outlined on the map, and the corresponding views are updated. These include the Country Overshoot card, Overshoot Indicator, Number of Earths Needed, Biocapacity Breakdown, Ecological Footprint Breakdown, Evolution of Ecological Footprint, Overshoot Timeline Chart, and Overshoot Calculator. This enables direct comparison of the selected country to Germany and the world.

Primary user actions include selecting a country on the map or dropdown, year selection, toggling the timeline, and adjusting scenario sliders. Other interactions include hover tooltips for graphs, map regions, and info icons that appear on the top right corner of each view for contextual explanations. The map view also offers a reset button, a zoom to Europe button, and a color legend. The Evolution of Ecological Footprint, Overshoot Calculator, and Timeline View of Sectoral CO_2 Emissions and Energy Consumption are accessible via navigation buttons, providing users with more detailed environmental visualizations.

Overall, the interaction flow supports intuitive and exploratory engagement, allowing users to transition smoothly from global patterns to national insights, test scenarios, and explore sector level implications. The design reflects the system's goal of transforming static environmental data into a responsive and engaging tool, with minimal user friction and a structured flow aligned with the information hierarchy established in the design goals.

3.4 User workflow and Use cases scenario

The following use cases illustrate how various users might interact with the platform. Although this analysis is not based on formal usability testing, it demonstrates how the system facilitates varying levels of engagement with Germany's Ecological Overshoot Day and associated sustainability indicators.

Use Case 1: Public exploring National impact

User: A person interested in environmental sustainability

The user begins on the homepage and decides to explore Germany from the map. They observe that Germany's Overshoot Day occurs significantly earlier than the global average and decide to explore the reasons. When scrolling down further, they view the historical timeline of Germany's Overshoot Day and notice a long term trend toward earlier dates. In the sectoral breakdown, they identify the corresponding sectors that contribute to Germany's overshoot day. The user then moves to the scenario simulator and adjusts the sliders to observe a shift in the Overshoot Day.

Use Case 2: Educator teaching Overshoot concepts in a classroom

User: A high school teacher explaining global resource consumption

The teacher uses the world map to show differences in Overshoot Day across countries and to illustrate the concept of ecological overshoot. The teacher chooses France from the world map and compares it with Germany and the world average using the timeline chart of overshoot days. The class discusses which countries consume more resources. The teacher then scrolls to the sectoral emissions view and asks students to interpret which sectors have the largest impact. The teacher then demonstrates how small changes in emission levels can delay the Overshoot Day, using the sliders in the simulation interface.

4 Implememtation

This chapter details the implementation of the visual analytic system, translating the design concepts from 3 into a functional application. It outlines the dataset preparation, the development of backend and frontend components, and the visualization components. The chapter concludes with an overview of the integration and deployment processes.

4.1 Data preprocessing

The accuracy and reliability of the visual analytic system depend on the quality and consistency of its input data. The system was developed only using publicly available and official datasets to ensure transparency and robustness. The primary data sources are:

- **Global Footprint Network (GFN):** GFN provides per-capita ecological footprint and biocapacity data in global hectares (GHA) with a sectoral breakdown, including cropland, forest products, grazing land, built-up land, carbon, and fishing grounds for most countries. (Global Footprint Network, n.d. b)
- **National Ecological Footprint and Biocapacity Accounts (NEFBA):** This is the data source used by GFN. This was used as a reference to cross-check and verify the data obtained from GFN. (Ecological Footprint Initiative, n.d.)
- **Umweltbundesamt (UBA – German Environment Agency):** Publishes official statistical data on sectoral carbon emissions, covering major sectors such as agriculture, transport, industry, and buildings. (Umweltbundesamt, n.d.)
- **Arbeitsgemeinschaft Energiebilanzen (AG Energiebilanzen - AGEB):** Provides energy balance data, particularly sectoral energy consumption, which was used to link energy consumption with CO_2 emissions.(Arbeitsgemeinschaft Energiebilanzen (AGEB), n.d.)

The datasets were cleaned to remove missing values, and the spreadsheets were converted into CSV format for efficient access by the backend system. The columns and rows were adjusted as required and harmonized into consistent measurement units. All energy values were converted to petajoules for consistency, and CO_2 emissions were standardized to kilotonnes (Kt). The available data records for Germany were between 1961 and 2024 for ecological footprint and Overshoot Day. And, between 1990 and 2024, for sectoral emissions and energy consumption. The share of indirect emissions from the energy industry was allocated and added to the corresponding sectors based on their percentage shares as provided in the UBA dataset. Additional fields, such as ecological footprint, were computed based on changes in carbon emissions to support the scenario simulator.

4.2 Backend Implementation

4.2.1 Overview

The backend of the system was implemented using **FastAPI**, which exposes a RESTful interface. The design ensured that data management, computations, and communication with the frontend were handled in distinct layers. The backend is responsible for serving the preprocessed datasets, performing computations for scenario simulation, and delivering structured responses to the frontend in a consistent format.

The API exposes several primary endpoints that deliver data to support the frontend visualization. Some other endpoints supply time series data for the timeline and sectoral visualizations. A separate endpoint accepts user-defined scenario parameters, such as modifications to sectoral emissions, and returns the computed impact on Overshoot Day. A forecasting endpoint merges historical and projected values to provide a unified view on the frontend. Data access and transformation are carried out in a dedicated service layer, where preprocessed datasets in CSV from the cloud storage are filtered and loaded using **Pandas**. The application runs on **Uvicorn**, a high-performance ASGI server that provides asynchronous execution.

4.2.2 Service Structure

The backend consists of four modular API classes, each of which has a set of endpoints within the FastAPI application:

- **CountryApi** provides country level indicators, including ecological footprint and biocapacity. It supports both yearly datasets and country specific time series for comparative analysis.
- **PieChartApi** is responsible for sectoral decomposition data. It provides access to energy consumption and carbon dioxide emissions in formats optimized for pie charts and drill-down visualizations.
- **ScenarioApi** implements interactive simulation capabilities. It offers endpoints for generating energy splits and accepting value changes from the slider to execute scenario based simulations.
- **ForcastApi** supplies the past Overshoot timelines and Machine learning output. It integrates historical and predicted values into a unified data series.

4.2.3 Core Functionality

- **Country-level indicators:** Country endpoints provide flexible access to ecological footprint and biocapacity. The route `GET /country/all/{year}` returns the full set of indicators for a year, while `GET /country/ct/{country_code}` delivers country specific series. These outputs drive the core components of the system, including the world map and its related components, timeline charts, the Evolution page's EF vs. BC charts, and the Calculation page's formula walk-throughs.
- **Sectoral composition:** The pie chart API supports both aggregated retrieval (`GET /pie_data/all`) and year-specific breakdowns (`GET /pie_data/energy`, `GET /pie_data/co2`). Responses are preformatted for Highcharts and include drill-down subsectors.
- **Scenario simulation:** The endpoint `POST /energy-split/simulate` accepts a scenario payload and percentage adjustments for five carbon emission sectors: agriculture, buildings, industry, transport, and waste. The backend recalculates the carbon component of the ecological footprint and returns both baseline and simulated Overshoot Days, as well as `delta_days`, which quantifies advancement or delay.
- **Forecasts:** The forecasting endpoints (`GET /forcast/`, `GET /forcast/all_e`) provide Overshoot Day timeline. Each record includes the year, calendar date, day-of-year (DOY), and an `is_predicted` flag, allowing the frontend to render observed and modeled data as a continuous series.
- **Validation and security.** All routers validate requests and responses using **Pydantic** models to enforce type integrity. Errors are managed as invalid input results in a `422` response, missing data in a `404` response, and unexpected conditions in a `500` response with server-side logging. Cross-origin resource sharing (CORS) validation and API key authentication ensure that the backend remains robust, private, and secure.

4.3 Frontend Implementation

4.3.1 Overview

The frontend of the system was developed using **Next.js**, which is a React-based framework that combines modular component development with server-side rendering. This choice enables more library support for visualizations, efficient routing, and fast navigation between views. State management was handled locally at the component level, providing sufficient flexibility for coordinating user interactions such as dropdown selections, scenario sliders, and map navigation.

Visualization was achieved using the **Highcharts** library, which provided responsiveness, interactivity, and accessibility for both time-series and hierarchical data. It includes built-in features such as tooltips, zooming, highlighting, and drill-down interactions that were integrated into multiple parts of the interface. Highcharts components were extended with custom logic to ensure integration of dynamic user inputs. **Tailwind CSS** was used to further design the system with consistent font sizes, alignments, legends, and color encodings across the system. These design choices together make the frontend interactive and accessible, enabling users to explore the raw data of overshoot and its drivers through an engaging interface.

The application is organized into four page views. The Home page offers an entry point and narrative context, introducing users to Overshoot Day and its underlying factors through a timeline of historical Overshoot Days, sectoral views presenting energy consumption and CO_2 emissions in a pie chart, and a line chart of the overshoot day forecast. The Evolution page view displays the timeline of biocapacity versus ecological footprint using a race chart. The Calculation view displays how the Overshoot day is calculated . The Data Details page offers a comparison between Germany's CO2 emissions and energy consumption on a line chart.

The frontend communicates with the backend through a private REST API developed using FastAPI. Data exchanges are structured as JSON over HTTPS. Cross-Origin Resource Sharing (CORS) validation is configured on the server to permit requests exclusively from the production frontend origin. This architecture ensures secure data transfer and prevents unauthorized access to backend endpoints.

4.3.2 Service Structure

The frontend utilizes a modular architecture, with each page composed of reusable components for visualization, interaction, and data access.

Highcharts was used to implement visualization. It supports multiple chart types, including line, area, and pie charts with drill-down functionality. Custom logic was implemented in these components to bind dynamic user input, such as year selection and sectoral percentage adjustment, directly to backend responses. Interactions rely on dropdown selectors and sliders. Year selectors let users examine specific evolutions, and sector sliders facilitate scenario adjustments by mapping each slider to a percentage share of the carbon component within the ecological footprint.

All data exchange was managed through a minimal API client. This client encapsulated fetch calls, appended the backend base URL, managed JSON serialization and deserialization, and standardized errors into a consistent structure. Data contracts were aligned with the backend OpenAPI specification and reinforced by TypeScript types for consistency. Most interactions were confined to the local component state and cross-page metadata, such as country lists and available years, which were included in page modules.

4.3.3 Functionality

We designed the frontend to preload large datasets and allow the UI to select data as required for each visualization. For instance, we used `GET /country/all/{year}` to retrieve all country level indicators, followed by targeted requests such as `GET /country/ct/{country_code}` for specific charts and comparisons. Sectoral aggregates were loaded with `GET /pie_data/all` for use in the energy and CO_2 pie charts. Historical and forecasted Overshoot Days data were combined using `GET /forcast/all_e`. For interactive simulations in the Calculation view, the frontend sent `POST /energy-split/` requests, enabling users to adjust sliders and see real-time updates to the Overshoot Day. This reduced unnecessary network requests and improved app responsiveness.

4.4 Visualization Components

4.4.1 World map overview

The world map has been designed as the Hero Section system with the goal of providing a geographic exploration and providing a global context for Overshoot Day data. **A choropleth map** was chosen to enable users to easily identify and compare countries visually. A sequential color grading has been used with darker shades representing earlier overshoot days and lighter shades indicating later dates. This color encoding was selected to match the dark mode of the user interface.The map also includes a 'Zoom to Europe' and 'Reset View' buttons. Additionally, an information button is provided on the world map card and throughout each component in the system to explain conceptual terms, such as Biocapacity. The data sources used for the visualisations have also been included.

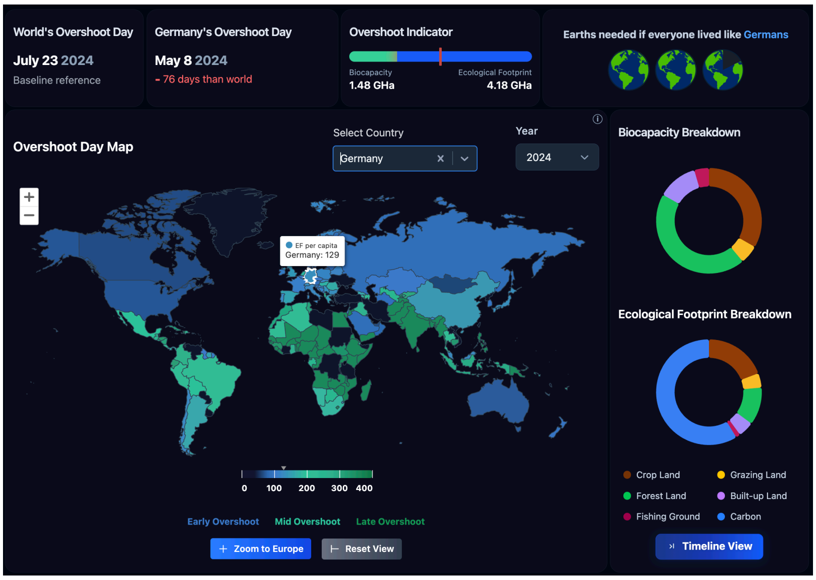

Figure 4.1: Overshoot Map

Users can select a country either from the map or the dropdown menu. The system then dynamically updates all connected components to reflect the data from the chosen country. This component design supports a coordinated view of information across multiple visual elements, creating a smooth exploration experience.

A set of several indicators has been displayed alongside the world map as in figure 4.1. The World Overshoot Day card shows the Global Overshoot Day as a baseline for comparison. The country overshoot day card displays the selected country's Overshoot day and highlights the difference from the global date in terms of the number of days, using green text if the country performs better and red if it performs worse. The **Overshoot indicator** card, in figure 4.2 visualizes the country's ecological footprint and global biocapacity, with a threshold line indicating the point at which ecological overshoot occurs. This is also indicated on the bar as 'Overshsoot' or 'No Overshoot' to avoid any scope for confusion when hovering as shown in figure. It also displays the Earth's per-capita Biocapacity and the per-capita Ecological footprint of selected country in GHA.

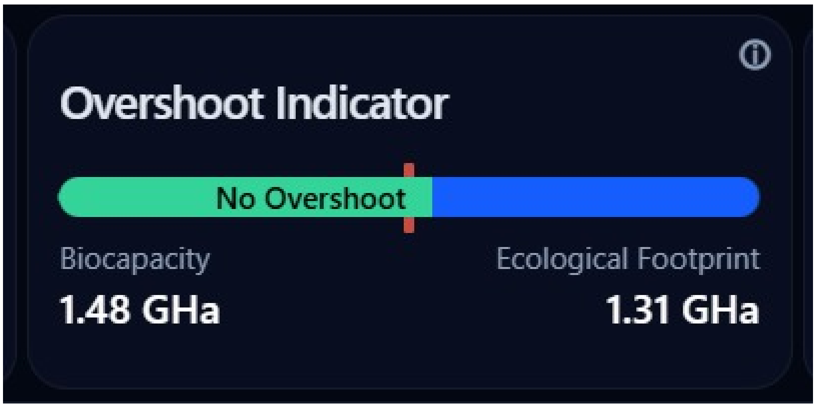

Figure 4.2: Overshoot Indicator

The Number of Earth card expresses ecological footprint in terms of how many Earths would be required if the entire global population were to adopt the lifestyle of the selected country. This has been implemented using multiple images of Earth as metaphors to convey the message of overshoot. Due to UI constraints, if the people of a country require more than five Earths, it is displayed with the corresponding Numerical value and an image of the Earth, as shown in the figure 4.3.

4.4.2 Donut Charts: Biocapacity and Ecological Footprint Breakdown

Two donut charts depict the sectoral breakdowns for Biocapacity and Ecological footprint. Each segment in the chart represents one of the six contributing land usage categories: cropland, forest land, grazing land,

Figure 4.3: Number of Earths needed

built-up land, fishing grounds, and carbon. Donut charts were chosen because they provide a straightforward way to represent part-to-whole relationships, making it easier for users to compare the relative area of different categories. The charts were implemented to be interactive. Each segment gets highlighted when the user hovers over it, and the other segments are dimmed for better focus. A tool tip then displays the corresponding value in global hectares per person. This approach keeps the visualization uncluttered while providing precise data on demand. These features enable users to directly compare ecological supply and demand for the selected country, supporting a more detailed understanding of Overshoot Day by highlighting both the overall ecological imbalance and the main contributing land usage categories.

4.4.3 Timeline chart

A time-series line chart, figure 4.4 displays the evolution of Germany's Overshoot Day from 1961 to 2024. This helps illustrate temporal trends and long-term changes. The global Overshoot Day serves as a baseline, allowing users to assess and compare if Germany is moving closer to or further away from the global average. Users can also select any country from the map or the dropdown menu and compare its trajectory with the global trend and Germany. The interactive legend allows users to toggle Germany's line on or off, highlight, or isolate specific series. This supports focused analysis, enabling users to observe long-term patterns.

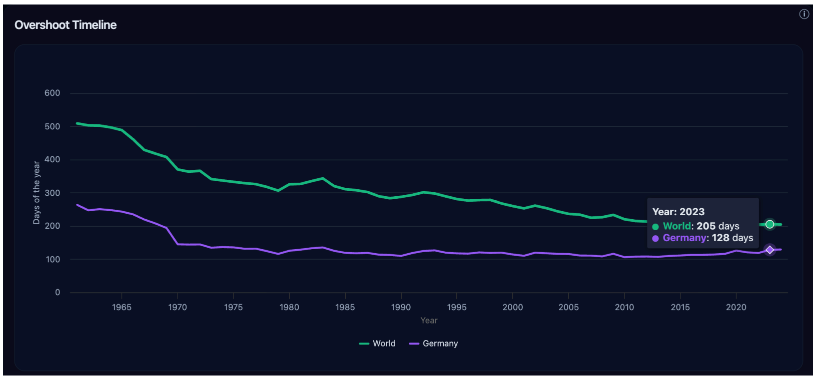

Figure 4.4: Overshoot Timeline

4.4.4 Sectoral Contribution Visualization

A two-level interactive pie chart was implemented to represent the contributions of different sectors to Germany's CO_2 emissions. Pie charts were chosen over the initially considered sunburst charts because they offer a more familiar and faster understanding of data. Initial developments showed that a simpler design improved readability and reduced cognitive load, especially for users with limited experience in interpreting multi-level hierarchical visualizations.

The two-level structure, figure 4.5 allows users to first view an overview of the four major sectors, which are industry, transportation, agriculture, and buildings, and then interactively drill down into their respective subsectors.The charts were provided with a shadow effect while hovering to make the user aware of the interactivity included. This stepwise exploration avoids overwhelming the user with excessive information at once and supports the development of a clear mental model of the emissions breakdown.

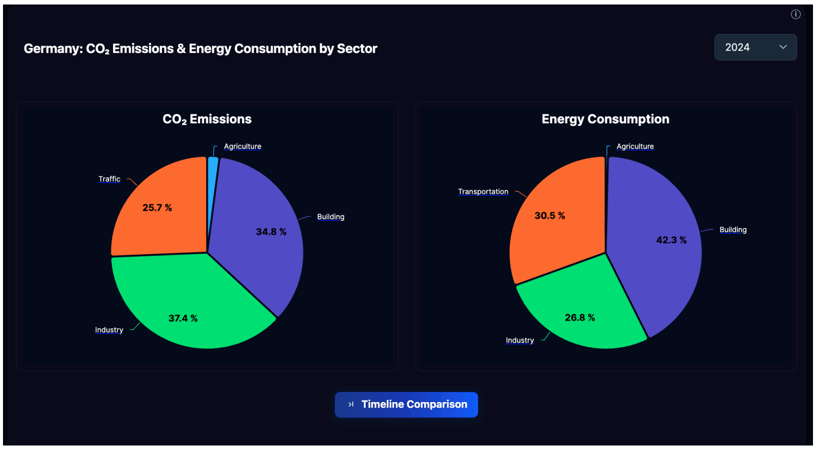

Figure 4.5: Sectorwise CO_2 emission and energy consumption

To enhance the analytical value of this component, a pie chart was included to display energy consumption across the same four sectors. When a sector is selected, its energy mix is revealed, allowing users to examine the relationship between energy use and its corresponding emissions. This pairing of emissions and energy consumption visualizations helps users identify which sectors and energy sources offer the greatest potential for targeted interventions.

4.4.4.1 Sectoral Comparison Timeline: CO_2 Emissions and Energy Consumption

Two timeline charts display trends in CO_2 emissions and energy consumption for four primary sectors in figure 4.6. The timeline can be accessed directly from the sectoral contribution charts.

The visualization features two adjacent line charts: one representing CO_2 emissions in kilotonnes and the other depicting energy consumption in petajoules. This arrangement highlights temporal changes and enables comparison of sector trends to identify potential correlations.

Sectors can be toggled on or off to enable focused comparisons. Disabling a sector in one chart automatically conceals it in the other to maintain consistency. The charts are integrated using brushing and linking techniques. Hovering over a sector legend in one chart highlights the corresponding sector in the linked chart. Tooltips display values for the selected year. These interactions enable users to analyze the relationship between energy use and emissions within each sector.

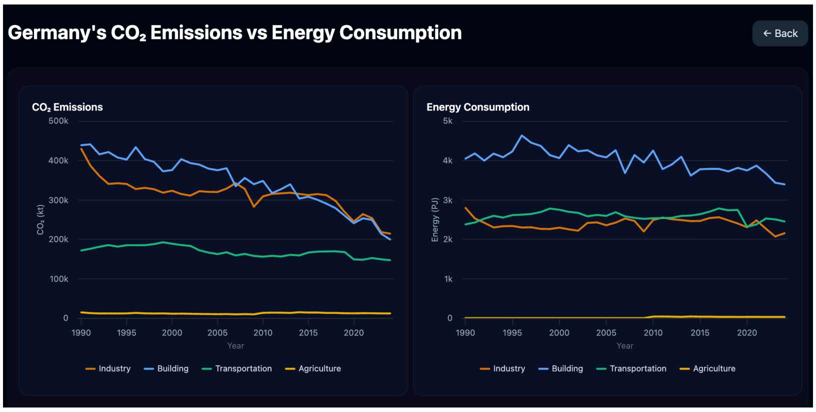

Figure 4.6: Sectorwise timeline of CO_2 emission and energy consumption

4.4.5 Scenerio Simulator

The scenario simulator was designed to make the impact of sectoral emissions on Overshoot Day both interactive and intuitive. Sliders are selected as the primary interaction mechanism through which users can adjust sectoral emissions and continuously observe the changes in real time. This enables experimentation and a deeper understanding of Overshoot Day in different sectors. This approach supports the exploratory analysis and provides an engaging way to test hypothetical scenarios.

The output is visualized using a dual calendar view as shown in figure 4.7 where the first calendar shows the Overshoot Day of the selected year as present. The second calendar displays the simulated Overshoot day after applying user-defined changes. Calendars were chosen because dates are in an easy to interpret format, without requiring additional explanation, making the shift in days of overshoot visually obvious. This approach makes the consequences of emission changes easier to perceive than a simple numeric display.

Three summary cards are presented above the calendars. The first card displays the present date, the second the simulated date, and the third highlights the difference between them expressed in days. Color hues have been encoded to communicate better interpretation, with positive shifts or delays in overshoot being shown in green, and negative shifts

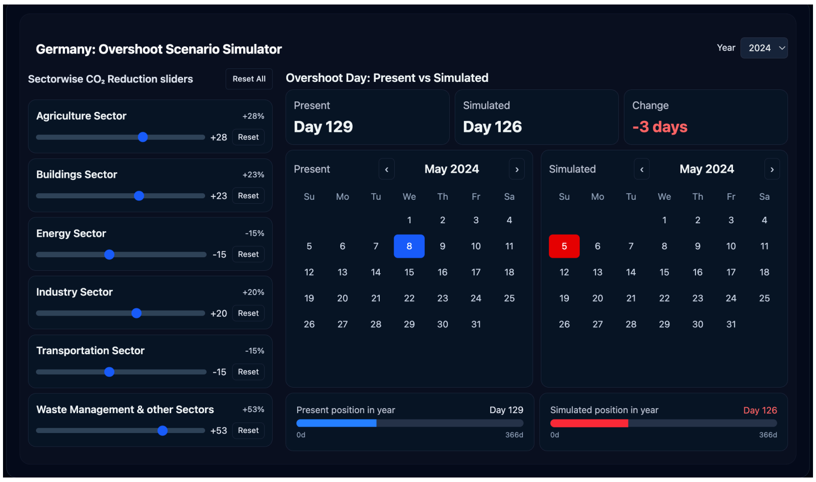

Figure 4.7: Overshoot scenerio simulator

or earlier overshoot days are shown in red. This color coding provides an immediate visual signal of whether the scenario has a beneficial or unfavourable effect. When combined, these decisions create an intuitive simulation interface that encourages exploration while clearly communicating the impact of sector-level emissions.

4.4.6 Forecasting component

The forecasting component, figure 4.8 lets users explore possible future trajectories of Germany's Overshoot Day based on historical data. The implementation is displayed using a line chart because it effectively communicates temporal trends and, at the same time, allows both observed and forecasted values to be shown in a continuous view. The forecast is represented as a dotted line that extends from the last available point in the dataset. This makes the uncertainty in visualization visible while still indicating the potential trajectory if current patterns persist.

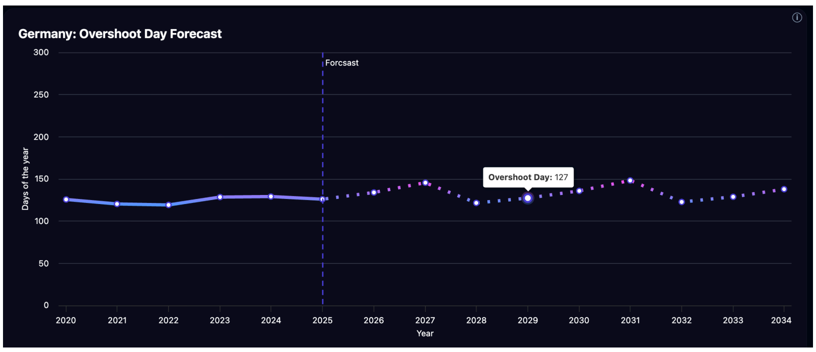

Figure 4.8: Overshoot forecast

The forecast uses the Facebook Prophet model, which is a time-series forecasting method suited for handling nonlinear trends and irregular patterns. The model was chosen over the popular ARIMA model because it requires minimal parameter tuning and performs robustly on relatively small datasets. The predictions have been calculated up to 2034 to balance relevance with the historical record and avoid suggesting unrealistic certainty.

Through this visualization, users can compare observed and projected data to assess whether Germany's historical trajectory points toward improvement, stability, or continued ecological overshoot in the coming decade.

4.4.7 Ecological Footprint vs. Biocapacity Timeline

Users can access a timeline view that plots the Ecological footprint per person against the biocapacity per person for the selected country directly from the donut chart component. The timeline, in figure 4.9 displays Germany alongside the global biocapacity and global ecological footprint, but the view dynamically updates when another country is selected through the map or dropdown. A line chart was chosen for this component because it provides a clear representation of long-term temporal changes, enabling users to identify the exact points at which ecological demand surpasses ecological supply.

The timeline spans the period from 1961 to 2024, with three legends: World Biocapacity, World Ecological Footprint, and the Ecological Footprint of the selected country. Tooltips provide GHA/person values for each timeline, and distinct color encodings ensure that the indicators remain visually distinguishable. Users can toggle each timeline on or off via the legend, allowing comparisons such as a country's ecological footprint against global biocapacity, or against the global footprint alone, without visual clutter. In general, ecological overshoot is indicated whenever a country's ecological footprint curve intersects and rises above its biocapacity. To clearly depict this, a race animation is applied to the line chart. For the world, this occurs when the global ecological footprint exceeds global biocapacity.

This visualization extends the functionality of the world map and donut charts by linking geographic selection with historical trends. It allows users not only to see when a country enters ecological overshoot but also to determine whether this condition results from a rising footprint, declining biocapacity, or both.

The map and the supporting cards together create a comprehensive overview that explains country level data within a global perspective, enabling users to quickly assess performance and focus on areas of interest for deeper exploration.

4.4.8 Overshoot Flow Diagram

A custom-built flow diagram demonstrates the calculation of Overshoot Day for 2024. This visualization was developed for this project without the use of external libraries. The diagram is accessible directly from the Overshoot Day timeline graph for any country selected from the map or dropdown menu.

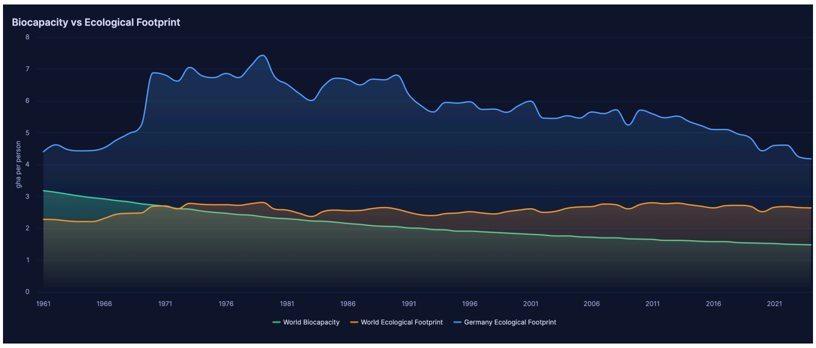

Figure 4.9: Timeline: Biocapacity vs Ecological footprint

Figure 4.10 down biocapacity and ecological footprint into land usage categories. Biocapacity includes cropland, forest land, grazing land, fishing grounds, and built-up land. The ecological footprint includes these categories and carbon, a primary contributor to overshoot. Each category's contribution is quantified in global hectares (GHA) per person, allowing comparison of the relative impact of each land usage type on a country's ecological balance.

Category values are aggregated to calculate total biocapacity and total ecological footprint. These totals are then used in the standard Overshoot Day formula:

$$\text{Overshoot Day (day of year)} = \frac{\text{Biocapacity}}{\text{Ecological Footprint}} \times 365$$

The flow diagram explicitly links category level inputs to aggregated totals and then to the Overshoot Day as a calendar day. For instance, in Germany for the year 2024, a biocapacity of 1.48 GHA per person and an ecological footprint of 4.18 GHA per person result in an Overshoot Day on the 129th day of the year, May 8, strictly based on the values in the available dataset.

This approach helps users understand the overshoot calculations, making them more transparent and facilitating better comprehension.

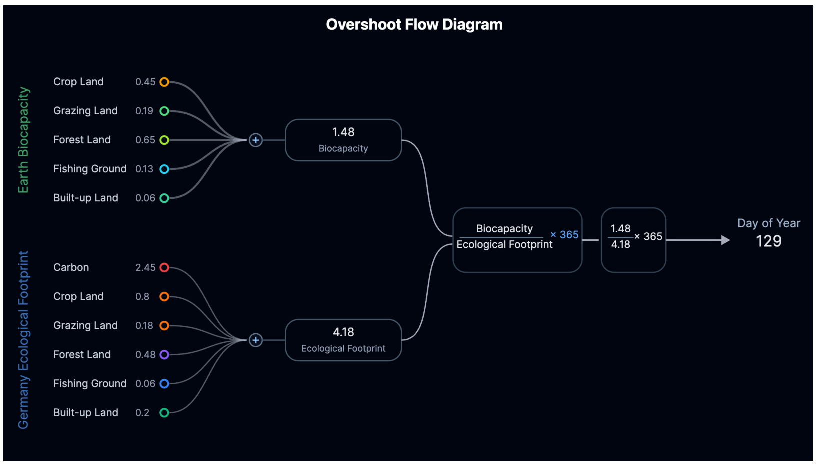

Figure 4.10: Overshoot calculator

4.5 Design Rationale

Each design choice, from visualization type to interface layout, was made to reduce cognitive complexity while maximizing perception, ensuring that the platform is not only informative but also visually appealing and engaging.

Line charts were selected for all historical timeline views due to their familiarity and interpretability, especially for visualizing temporal trends such as changes in Overshoot Day, biocapacity, and ecological footprint. Among the available options, line charts offer a direct and minimal way of comparing values across time without overwhelming the user (Munzner, 2014). **For sectoral decomposition**, pie charts were used instead of more complex hierarchical charts (e.g., sunburst), since the available data only required two levels of representation. The pie chart provided a more aesthetically cohesive fit within the UI and allowed users to grasp proportional contributions at a glance without additional explanation. **The race chart** visualization was introduced to present historical changes in sector contributions over time in a dynamic, engaging manner. Compared to static bar or line charts, race charts capture user attention and emphasize rank changes and convergence or divergence among categories, which helps users grasp temporal dynamics more vividly. This aligns with cognitive principles that suggest animated transitions aid in understanding change over time.

The most strategically significant visual element is the **Overshoot Indicator bar**. This visually minimal and compact visualization that encapsulates the entire concept of ecological overshoot in an immediately comprehensible form, with biocapacity and ecological footprint as adjacent segments on a single scale. Even without further interaction with the dashboard, a user can understand the core sustainability challenge by interpreting this indicator. It communicates the imbalance between ecological supply and demand at a glance. **The "Number of Earths" indicator** is another core component, which visualizes how many planet Earths would be required if everyone lived with the same consumption patterns as the selected country. This metaphor translates abstract sustainability metrics into an easily comprehensible form by visually duplicating Earth icons to represent ecological demand. Depicting more than one Earth and sometimes in fractions, confronts users with the unsustainable lifestyles. This enables even non-technical users to grasp the significance without needing to decode technical terminology. When paired with the Overshoot Indicator bar, this component reinforces the system's goal of transforming complex ecological data into accessible and actionable insights.

The design also uses best practices observed in interactive dashboards from other domains, but pushes them further by emphasizing Germany. Many existing dashboards are technically rich but either visually cluttered or difficult to navigate for general users. The overall view is structured to follow a global to national and historical to forecast progression. Each visualization includes contextual information buttons to ensure that even those without prior exposure to ecological footprint concepts can engage meaningfully with the data. **A dark theme** was adopted for the application interface to enhance contrast, improve aesthetic appeal, and align with modern UI trends commonly used in mobile and desktop environments. The dark background allows bright chart elements to stand out, making tooltips and interactive highlights more noticeable. The use of red–green combinations has been minimized, as they may cause accessibility issues, but some limited use was kept for visual emphasis in specific cases.

Interactivity, incorporating hover tooltips, toggles, and sliders, was prioritized over more complex dropdown menus or filter panels to ensure simplicity and ease of use. This decision reflects the project's focus on serving the general public. The design encourages users to engage, experiment, and learn without requiring deep technical expertise or prior environmental knowledge.

Overall, the system reflects a design rationale that balances analytical depth with usability, drawing from established visualization principles, literature on interactive sustainability tools, and user-centered design practices. It not only fills gaps identified in the academic review but also aims to create a positive and empowering data experience where users feel informed.

4.6 Integration and Deployment

The developed system integrates the frontend and backend into a publicly accessible web application. The frontend, implemented with **Next.js**, handles visualization and user interaction, while the backend, implemented with **FastAPI** in Python, provides data management, forecasting, and scenario simulation functionalities. RESTful APIs handle the communication between the two layers.

Data integration was achieved by consolidating ecological and energy related datasets from sources: Global Footprint Network, Umweltbundesamt, and AG Energiebilanzen. These preprocessed datasets were standardized into CSV format and stored in cloud storage to ensure efficient and consistent access. The backend API loads these files on demand, processes queries, and sends structured JSON responses to the frontend, which then renders the results through interactive Highcharts components.

For deployment, the **frontend** was hosted on **Netlify**, which allows automatic builds and continuous deployment directly from the GitHub repository. This ensures that updates to the codebase are quickly reflected in the live system. The **backend** was deployed on **Google Cloud Run** using the Google Cloud CLI. This serverless architecture supports seamless integration with cloud hosted datasets. Containerization ensures the reproducibility of the backend environment, and environment variables and configuration files are used to securely handle credentials and cloud access.

The outcome is a stable and accessible application available at https://overshoot-germany.netlify.app/. Users can interact with the system directly from their browsers without requiring any installation or technical expertise. This deployment strategy ensures that the system is usable for a broad audience, including researchers, educators, and the general public, and provides a strong foundation for future extensions.

5 Evaluation

The evaluation assessed the clarity, interpretability, usefulness, and overall impact of the developed visual analytics system. The primary goal was to determine whether the system aligns with the design objectives outlined in Chapter 1, which focused on understanding the ecological overshoot, enabling scenario-based exploration, and visualizing Germany's sectoral overshoot drivers.

5.1 System Validation

The system validation focused on assessing how effectively the system performed when tested by users and whether it supported the intended goals. The evaluation setup, task design, and participant selection are described in the following subsections.

5.1.1 Evaluation Setup

The evaluation was conducted as a self-guided remote study using a structured survey. Participants were provided with the application link and instructed to explore the system independently at their own time and pace. Each participant completed a list of seven predefined tasks focused on the major components of the interface. The survey was designed to ensure meaningful engagement and support the collection of qualitative and quantitaive feedback.

The evaluation was conducted anonymously with consent for use of responses for academic research. No personal data was collected during the process

5.1.2 Evaluation Tasks

The tasks included in the survey were:

1. **World Map**: Use the map to change the focus to Europe and find the Overshoot Day of any European country.
2. **Overshoot timeline**: Find the World Overshoot Day for 2014 (e.g., 128th day) and identify how France can be compared to the world average and Germany in the same year.

3. **Read the timeline view**: Does Germany's ecological footprint trend go up or down since 1990?
4. **Compare sectors**: In 2024, which sector and its subsector contributes most to Germany's CO_2 emissions?
5. **Compare sectors**: In 2024, which sector and its energy source consume the most of Germany's energy consumption?
6. **Scenario simulator**: Reduce "Traffic" and "Building" by 20% and report the new Overshoot Day change (in days).
7. **Forecast**: In which future year does the forecasted Overshoot Day reach its highest?

These tasks were chosen to align directly with the system's main features and design goals as discussed in Chapter 3.

5.1.3 Participants

Ten participants were chosen from different expertise and backgrounds. Two participants had a background in computer science and visualization, two were from the sustainability domain, one was a researcher or data analyst, and the remaining five participants represented the general public with minimal prior exposure to Overshoot Day or sustainability tools. The diversity of the participants was intentional, as the platform was designed to be accessible to a broad audience, primarily to educate the general public, while also being engaging for educators and researchers.

5.2 Quantitative feedback

The survey included questions where the participants evaluated specific aspects of the system on a 10-point Likert-style scale (1 = very poor, 10 = excellent). This enabled the collection of quantitative data regarding users' perception of the system's usability and interpretation.

Quantitative results indicated a high level of user satisfaction with the system. Visualizations were rated highly for usefulness, with an average score of 8.9 out of 10 as shown in Table 5.1. The scenario simulator and timeline view received the most favorable evaluations. The system's ease of use was rated at 8.3. This reflects positive assessments of the interface and minimal learning curve. Aesthetic appeal received an average score of 9.1, with participants liking the dark theme, color contrast, and clean layout. Trust in the forecast averaged 7.6, indicating general acceptance and identifying a need for better transparency regarding forecast calculation methods. Clarity of legends and labels received a score of 7.8. Some participants reported initial minor confusion with pie chart color gradients and sector terminology, but this was later resolved by viewing the information buttons.

Table 5.1: Average user ratings (1–10 scale)

Aspect	Mean Score	Comments
Usefulness	8.9	Timeline and simulator most appreciated
Ease of Use	8.3	Minimal learning curve, clear navigation
Aesthetic Appeal	9.1	Dark theme and contrast praised
Trust in Forecast	7.6	Needed transparency in calculation methods
Clarity of Labels/Legends	7.8	Some confusion with pie chart gradients and sector terms

5.3 Qualitative Findings

The survey also included open-ended questions to gather qualitative insights into the user experience. These questions focused on specific aspects, such as the visual design and color scheme, the clarity and usability of interface elements, and overall feedback, including likes, dislikes, suggestions for design improvement, and new features. This approach helped to understand the participants' perceptions and usability issues as well as recommendations for future improvements. The qualitative data provided context that supports and complements the quantitative findings, enabling a more thorough evaluation of the system's effectiveness and user-centered design.

Users found the interface to be visually appealing yet simple to use. Many described the experience as "engaging" and "well-structured." The Overshoot Indicator and the Number of Earths display were said to be particularly effective in conveying the core message of ecological overshoot in a simple and impactful manner. The calendar-based output of the scenario simulator was easy to understand, allowing users to immediately observe how small changes in sectoral emissions could affect Germany's Overshoot Day. Participants also rated the interactivity and responsiveness of tooltips and sliders as helpful.

5.4 Discussions

From these results, the system design and implementation have succeeded in their design goals to an extent. Users from different backgrounds were able to complete the given tasks, interpret visual outputs, and derive insights without prior training. A sample survey response from one of the users is added in the Appendix A part for reference. This supports the system's goals of promoting awareness, fostering understanding, and enabling scenario-based exploration of Overshoot Day.

The strongest responses were about the scenario simulator on how it visually depicts the overshoot day shifts in a Calendar view. Improvements were suggested to provide more meaningful color encodings and forecast transparency. A few users expressed difficulties in understanding the drill-down features of the pie charts and suggested adding a back button to return to the main category, even though this was already implemented in the system. Some users suggested including options for manually entering slider values in the scenario simulator. One user was not able to find the information button, which appears only on hovering over each visualisation. Many users responded to the need to include a feature that enables comparison between different countries when asked for additional feature suggestions. Several enhancements could be planned based on user feedback.

In conclusion, the evaluation confirms that the system is both functional and impactful. It demonstrated strong usability, visual appeal, and effectiveness in communicating the complexities of ecological overshoot in a format that is accessible and engaging. These findings validate the system's contribution as a meaningful tool for understanding, simulating, and communicating Germany's Overshoot Day.

5.5 Evaluation Limitations

The evaluation had its share of limitations. The sample size was small and diverse, but large-scale testing would allow for more statistical conclusions. The assessment did not include a pre-assessment and post-assessment of the user‘s domain knowledge , which could be introduced in the future to measure learning outcomes more directly. Some users initially misunderstood the scale and interpreted lower numbers as positive ratings.

6 Conclusion and Futurework

6.1 Conclusions

This thesis describes the design and development of an interactive visual analytics system to help people better understand Germany's Overshoot Day. The primary outcome is an interactive dashboard that integrates historical, sectoral, and forecasted environmental data on a unified platform, supporting exploration, comparison, and scenario simulation. The system educates and raises awareness among the general public. For more informed users, such as educators and researchers, it provides a platform to engage with the concept of ecological overshoot in an accessible way through visual analytics.

The dashboard combines multiple perspectives on Overshoot Day, including global context, historical trends, sector-wise CO_2 emissions, scenario simulation, and forecasting. Despite limitations in data availability, all primary objectives of the proposed system have been implemented. This demonstrates the feasibility of building a comprehensive Overshoot Day platform for Germany, but also highlights the role of visual analytics in bridging the gap between complex sustainability metrics and public understanding. With the current version, a user can easily grasp what Overshoot Day is, where Germany stands in the global context, and how behavioral or sectoral changes could impact the country's ecological future. Overshoot day is calculated using data from GFN for 2025 and their official calculation formula. However, slight variations in the days appear when compared with GFN. This is mainly because data changes each year and GFN makes projections using preliminary estimates.

Working with modern web technologies, such as Next.js and the Highcharts library, provided a valuable experience in building a full-stack application with interactive visual tools. Highcharts allowed interactivity and ease of integration, offering better visualization capabilities than previously considered libraries. Unlike existing dashboards, this system provides an interactive environment that enables users to experiment with the factors influencing ecological overshoot and observe the results in real time.

6.2 Challenges and Limitations

The development process had several challenges. The most difficult and time-consuming task was finding, accessing, and integrating reliable environmental data. Contrary to the common perception that environmental datasets are easily available, the reality is that data are scattered across platforms, inconsistently formatted, or missing important details needed for deeper analysis. Understanding and harmonizing the data required significant effort.

A major challenge was understanding and establishing relationships between datasets to visualize them in multi-coordinated views while still conveying the message of ecological overshoot. A maximum number of visualizations has been implemented. Another goal was to create an interactive UI that keeps users engaged and is visually appealing.

During the integration and deployment process, several challenges were encountered. Aligning heterogeneous datasets into a common temporal and sectoral structure required extensive preprocessing. Ensuring consistent communication between asynchronous frontend requests and backend responses demanded careful testing. Configuring cloud services to balance performance, cost, and security also involved iterative refinements.

The designed UI was compact, leaving limited room for adding more interactive features. However, this is just the first implementation stage, and functionality can be added in future iterations.

6.3 Future Work

The implementation experience and the user evaluation results have together provided several directions for future work.

The system could be expanded to include more countries based on data availability. This would enable users to explore features like Overshoot Day timelines, sectoral contributions, simulations, and forecasts, which are currently available for Germany alone. Another major feature that could be implemented is the ability to compare any two countries in the world map component. Introducing the concept of "Country Deficit Day", which indicates when a nation's resource use exceeds its domestic biocapacity, could provide even more insights into sustainability challenges in a national context. Data could be made directly available within the application in a downloadable format rather than providing external source links.

Forecasting capabilities could also be enhanced by refining the models used and enabling forecasts under multiple user-defined scenarios, rather than relying on a single default trajectory based on historical patterns. Similarly, the scenario simulator could be improved by introducing more meaningful sliders, such as "conversion of vehicles to EVs," "increase renewable share in electricity generation," or "improve building insulation efficiency." This would make simulations more relatable to users and closer to policy design, which could be extended to policy-makers, environmental analysts, and sustainability planners by incorporating more detailed data, customizable simulation tools, and localized forecasting.

From a User Interface perspective, planned enhancements include offering both light and dark modes, supporting multiple device compatibility, and enabling multilingual access. These changes would broaden accessibility and appeal.

In conclusion, the thesis demonstrates the potential of visual analytics for improving the understanding of Overshoot Day in Germany. While the current prototype is limited in geographical scope and data depth, it provides a strong foundation for future expansion into global comparisons, richer simulation features, and broader accessibility.

Repository and Application Links

For further details and source code, please refer to the GitHub repository:
`https://github.com/eldho-se/overshoot-app`

The deployed application can be accessed at:
`https://overshoot-germany.netlify.app/`

A | Survey Results

An anonymized example of a completed remote user survey response is presented below to demonstrate the survey structure.

Overshoot Day Visual Analytics - User Evaluation

This survey evaluates the usability and clarity of the Overshoot Day Visual Analytics dashboard. Your feedback will help enhance the interface, color scheme, interactivity, and the effectiveness of the visualizations and simulator. The survey takes approximately 10 to 15 minutes. Most questions use a 1 to 10 scale, with a few short tasks and open-ended comments. Participation is voluntary and anonymous. Responses will be used solely for academic research and to inform design improvements. Thank you for helping us create a more effective visualization tool.

I consent to the use of my anonymous responses for academic research. *

- [x] Yes
- [ ] No

About you

These questions help us analyze results by experience level and usage habits. They are optional, anonymous, and used solely to interpret findings, not to identify you.

Q1. How familiar are you with ecological footprint, Biocapacity, Overshoot Day, and data on CO_2 emissions and energy consumption?

	1	2	3	4	5	6	7	8	9	10	
Not at all	○	○	○	○	○	○	○	○	○	◉	Expert

Q2. How frequently do you use data dashboards?

- ○ Never
- ○ Occasionally
- ○ Sometimes
- ○ Often
- ◉ Always

Q3. Your role

- ○ Computer Science Student
- ◉ Works or studies in Sustainability or related fields
- ○ Reseacher/Analyst
- ○ General Public

First Impression

Please rate your initial reaction to the dashboard **before doing any tasks**. Focus on overall clarity, how quickly you grasp its purpose, and whether the layout and density feel right. Don't overthink, go with your first instinct!

Q4. The overall interface looks clear and modern.

	1	2	3	4	5	6	7	8	9	10	
Strongly disagree	○	○	○	○	○	○	○	○	○	◉	Strongly agree

Q5. I immediately understood what this system is about.

	1	2	3	4	5	6	7	8	9	10	
Strongly disagree	○	○	○	○	○	○	○	○	○	◉	Strongly agree

Q7. The information density feels appropriate (not too sparse, not overwhelming).

	1	2	3	4	5	6	7	8	9	10	
Strongly disagree	○	○	○	○	○	○	○	○	○	◉	Strongly agree

Short task - 1

World Map: Use the map to change the focus to Europe and find the Overshoot Day of any European country.

Record your answer: Chosen country and date

Germany, May 8th 2024

Difficulty

	1	2	3	4	5	6	7	8	9	10	
Very easy	◉	○	○	○	○	○	○	○	○	○	Very hard

Short Task - 2

Overshoot timeline: Find the World Overshoot Day for 2014

(e.g., 128th day)

and identify how France can be compared to the world average and Germany in the same year.

Record your answer:

In 2014: World Overshoot Day: 205th day, France's Overshoot Day: 113th day, Germany's Overshoot Day: 129th day

Difficulty

	1	2	3	4	5	6	7	8	9	10	
Very easy	○	●	○	○	○	○	○	○	○	○	Very hard

Short task - 3

Read the timeline view: Does Germany's ecological footprint trend go up or down since 1990?

Record your answer:

Down

Difficulty

	1	2	3	4	5	6	7	8	9	10	
Very easy	●	○	○	○	○	○	○	○	○	○	Very hard

Short task - 4

Compare sectors: In 2024, which sector and its subsector contributes most to Germany's **CO_2 emissions ?**

Record your answer:

Industry, Manufacturing Fuel

Difficulty

	1	2	3	4	5	6	7	8	9	10	
Very easy	◉	○	○	○	○	○	○	○	○	○	Very hard

Short task - 5

Compare sectors: In 2024, which sector and its energy source consume the most of Germany's **energy consumption?**

Record your answer:

Building, Natural Gas and LPG

Difficulty

	1	2	3	4	5	6	7	8	9	10	
Very easy	◉	○	○	○	○	○	○	○	○	○	Very hard

Short task - 6

Scenario simulator: Reduce “Traffic” and "Building" by 20% and report the new Overshoot Day change (in days).

Record your answer:

135 dyas

Difficulty

	1	2	3	4	5	6	7	8	9	10	
Very easy	○	◉	○	○	○	○	○	○	○	○	Very hard

Short task - 7

Forecast: In which future year does the forecasted Overshoot Day reach its highest?

Record your answer:

2031

Difficulty

	1	2	3	4	5	6	7	8	9	10	
Very easy	◉	○	○	○	○	○	○	○	○	○	Very hard

Visualization-specific ratings

For each visualization below, rate **Readability**, **Usefulness**, **Clarity of legends/labels**, and **Aesthetic appeal**

World map of Overshoot Days:

	1	2	3	4	5	6	7	8	9	10
Readability	○	○	○	○	○	○	○	○	○	◉
Usefulness	○	○	○	○	○	○	○	○	○	◉
Legends/scale clarity	○	○	○	○	○	○	○	○	○	◉
Aesthetic appeal	○	○	○	○	○	○	○	○	○	◉

Comments

Overshoot Indicator:

	1	2	3	4	5	6	7	8	9	10
Readability	○	○	○	○	○	○	○	○	○	◉
Usefulness	○	○	○	○	○	○	○	○	○	◉
Legends/scale clarity	○	○	○	○	○	○	○	○	○	◉
Aesthetic appeal	○	○	○	○	○	○	○	○	○	◉

Comments

Timeline Charts:

	1	2	3	4	5	6	7	8	9	10
Readability	○	○	○	○	○	○	○	○	○	◉
Usefulness	○	○	○	○	○	○	○	○	○	◉
Legends/scale clarity	○	○	○	○	○	○	○	○	○	◉
Aesthetic appeal	○	○	○	○	○	○	○	○	○	◉

Comments

Donut Charts:

	1	2	3	4	5	6	7	8	9	10
Readability	○	○	○	○	○	○	○	○	○	◉
Usefulness	○	○	○	○	○	○	○	○	○	◉
Legends/scale clarity	○	○	○	○	○	○	○	○	○	◉
Aesthetic appeal	○	○	○	○	○	○	○	○	○	◉

Comments

Pie charts:

	1	2	3	4	5	6	7	8	9	10
Readability	○	○	○	○	○	○	○	○	○	◉
Usefulness	○	○	○	○	○	○	○	○	○	◉
Legends/scale clarity	○	○	○	○	○	○	○	○	○	◉
Aesthetic appeal	○	○	○	○	○	○	○	○	○	◉

Comments

Would be more better if there was a "back" button to go back to the main category from subcategory.

Overshoot simulator:

	1	2	3	4	5	6	7	8	9	10
Readability	○	○	○	○	○	○	○	○	○	◉
Usefulness	○	○	○	○	○	○	○	○	○	◉
Legends/scale clarity	○	○	○	○	○	○	○	○	◉	○
Aesthetic appeal	○	○	○	○	○	○	○	○	○	◉

Comments

The slider some time is hard to move to the very next value (eg from 19% to 20%). Better if there was also a '+' '_' to move the slider.

Forecast plot:

	1	2	3	4	5	6	7	8	9	10
Readability	○	○	○	○	○	○	○	○	○	◉
Usefulness	○	○	○	○	○	○	○	○	○	◉
Legends/scale clarity	○	○	○	○	○	○	○	○	○	◉
Aesthetic appeal	○	○	○	○	○	○	○	○	○	◉

Comments

Interactivity & controls

Rate how well the dashboard responds to your actions.

Q8. Country selection, year dropdowns, and "Reset view" were easy to find and use.

	1	2	3	4	5	6	7	8	9	10	
Strongly disagree	○	○	○	○	○	○	○	○	○	◉	Strongly agree

Q9. Tooltips and hover states revealed the right amount of detail.

	1	2	3	4	5	6	7	8	9	10	
Strongly disagree	○	○	○	○	○	○	○	○	○	◉	Strongly agree

Q10. The interface supports both exploration and quick answers.

	1	2	3	4	5	6	7	8	9	10	
Strongly disagree	○	○	○	○	○	○	○	○	○	◉	Strongly agree

Color & visual design

Assess the overall appearance: color selections, consistency across views, readability/contrast, and visual attractiveness.

Q11. Please share any aspects you like or dislike about the color scheme. Do you have any suggestions for improvement?

Everything looks good

Q12. Are the colors consistent across all views? If inconsistencies exist, please specify where they occur.

Everything looks good

Q13. Is the contrast between the text and legend clear and easy to read? If not, please specify which elements are hard to see.

Yes

Q14. Do any colors seem misleading or confusing? If so, please specify which colors and where they are located.

No

Performance

Rate how smoothly the dashboard runs.

Q15. The dashboard's features (navigation, filters, charts, simulator) function well together as a unified tool.

- ○ Strongly disagree
- ○ Disagree
- ○ Neutral
- ○ Agree
- ◉ Strongly agree

Q16. The system felt responsive with no noticeable lag.

- [ ] Strongly disagree
- [ ] Disagree
- [ ] Neutral
- [ ] Agree
- [x] Strongly agree

Q17. Are the units, dates (e.g., "Day 129"), and terms clear and easy to understand?

- [x] Yes
- [ ] No

Q18. Did any designs or text confuse you? If yes, how?

No

Q19. Was the "i" info button easy to find and helpful? If not, what changes do you suggest?

Yes

Q20. I encountered bugs or layout issues. If yes, please describe.

No

Overall verdict & open feedback

Give your overall rating and quick comments.

Q21. Overall rating of the system

1	2	3	4	5	6	7	8	9	10
○	○	○	○	○	○	○	○	○	◉

Q22. What did you **like most** and **least**?

I really liked the overshoot scenario simulator

Q23. If you could change one thing to enhance insight or usability, what would it be?

The slider sometimes is hard to move to the very next value (eg from 19% to 20%). Better if there was also a '+' '_' to move the slider.

Q24. Are there any features you'd like to see added (e.g., comparisons, explanations, more regions or years)?

The comparison is only possible between a country and the world average. Better if there is a possibility to compare two different countries or regions at the same time.

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Declaration of Authorship

In accordance with § 9 Abs. 12 APO, I hereby declare that I wrote the preceding master's thesis independently and did not use any sources or aids other than those indicated. Furthermore, I declare that contents and wording of both versions (digital and on paper) must be identical and that I am aware that this digital version may be subjected to a software-aided, anonymised plagiarism inspection

Bamberg, den ______________________ ____

Eldhose Abraham