Country-based Visual Analysis of Sustainable Energy Technologies and their Critical Raw Materials

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ABSTRACT

The following report introduces the bachelor project entitled *Country-based Visual Analysis of Sustainable Energy Technologies and their Critical Raw Materials*. The primary objective of this project is to create a comprehensive and interactive full-stack application for visualizing the country-based production, trade, and utilization of the critical raw materials demanded for the construction of sustainable energy technologies. The report encompasses the project's objectives, methodologies, data, implementation, limitations, as well as specific users-tasks and use-cases. Furthermore, it serves as a valuable point of reference for developing and assessing future works related to both the project and the thesis.

KEYWORDS

Data Visualisation, Sustainable Energy Technologies, Critical Raw Materials, Sustainable Energy Supply Chains

1 INTRODUCTION

In the contemporary era, the urgency of addressing the critical issue of global climate change has prompted the acknowledgment and adoption of sustainable energy technologies.

These are defined as energy sources that can be harnessed without depleting natural resources or causing significant harm to the environment, thus promoting long-term environmental, social, and economic well-being [2, 7].

This fact is evident from the widespread ratification of the Paris Agreement in 2021, where nearly 200 nations committed to limiting global temperature rise to below 1.5°C above pre-industrial levels [4, 5, 8]. As a result, sustainable energy technologies have become crucial political priorities worldwide. In Europe, policymakers are actively promoting measures to accelerate the transition, such as expediting permits for renewable energy power plants, boosting renewable hydrogen and offshore sources, encouraging alternative fuels, and revising funding rules for cross-border energy infrastructure projects.

Yet, sustainable energy technologies comprise a vast and complex system. At the beginning of this system, critical raw materials play a central role as the primary and essential elements for constructing the necessary components of these technologies. At the end of this mechanism, sustainable energy represent the direct and desired output of these technologies, which serves as an essential lifeline, providing heat, light, electricity, and fuel for transportation (Figure 1).

Critical raw materials are defined as natural resources used to produce goods of strategic economic importance with a high risk of supply disruption. For instance, copper is considered critical because its production is concentrated in two economically and politically unstable countries, as well as strategic because it is a key conductor within many electronic components, including the solar cells of photovoltaic solar panels [2, 7].

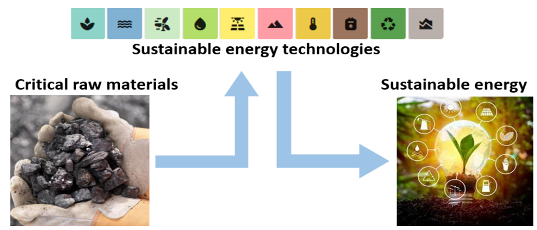

Figure 1: Sustainable energy technologies: their critical raw materials and sustainable energy

These critical raw materials serve as the backbone of sustainable energy technologies, influencing their construction and maintenance, as well as the production, trade, storage, utilization, and transformation of the energy they generate. For example, the production costs and material availability of copper directly impact the affordability of photovoltaic solar panels and the efficiency of solar energy.

Furthermore, critical raw materials significantly influence various aspects of our environmental, political, economic, and social systems. For example, countries possessing technological know-how and industrial capabilities but lacking abundant mineral resources may be more vulnerable to geopolitical dependencies, higher costs, and supply risks. On the other hand, countries rich in mineral resources may face environmental challenges such as air pollution and deforestation due to extractive activities.

Our project aims to develop an interactive full-stack application that empowers researchers, domain experts, and the general public to explore, identify, and analyze country-based characteristics, trends, and relationships of critical raw materials and sustainable energy related to sustainable energy technologies.

Our project's primary objective is to collect and visualize many different data in an interactive and user-friendly format, designed to meet requirements and tasks of the users.

By achieving this goal, we aim to assist researchers and domain experts in visualizing important data sets and gaining a deeper understanding of the intricate supply chain of critical raw materials. Furthermore, we aspire to use this user-friendly approach to educate the general public about the vital importance of these raw materials in the field of sustainable energy technologies. Ultimately, we hope that our application can potentially contribute to informed decision-making in both research and policy development, fostering a more sustainable and responsible energy landscape.

2 DATA CHARACTERISTICS

In this section, we will outline the process we pursued to collect, select, and merge the data sets, that serve as the fundamental basis of our project. Especially the data collection stands out as one of the most crucial and time-consuming components of our project.

2.1 Data sources and sets

As already mentioned the overall objective of the project was to visualize information on two key aspects related to sustainable energy technologies: country-based critical raw materials and sustainable energy.

2.1.1 Material-related data sources.
For gathering material-related information, our initial plan was to rely on the European Commission's Raw Materials Information System (RMIS), a web-based knowledge platform that provides data for the Raw Materials Supply Chain Viewer (SCV). The SCV is an interactive web application developed by [3] that visualizes the involvement of countries, minerals, sectors, and products in the supply chains of over 60 raw materials. We were particularly interested in insights about the type, location, and quantity of critical raw materials extracted and transformed to create products and components for sustainable energy technologies. However, due to the unavailability of publicly accessible data from the RMIS, we had to explore alternative databases to meet our research needs.

We discovered that the International Resource Panel provides information on the extraction, trade, and consumption of materials between countries from 1970 to 2019. However, their data set only considers material groups rather than specific minerals or materials (e.g. nonmetallic minerals, biomass, fossil fuels, and metal ores).

Another option we considered was Ecoinvent, which contains informationa resource that provides data on industries and agriculture, including the energy, materials, and products required for various processes. Unfortunately, accessing the data from Ecoinvent required purchasing a license.

Finally, we found *MineralsUK* and *IEA* to be reliable sources of information, which together provide similar material-related information to RMIS (Figure 2).

MineralsUK is as a comprehensive hub for mineral resource information and serves as the primary source of data for the leading global geoscience organization British Geological Survey. It provides data on the amount of material (measure in Tonnes) produced, exported, and imported for over 80 raw materials from 2003 to 2018 across 112 countries.

The *IEA* is a renowned international agency dedicated to shaping sustainable energy policies and holds wide recognition as a reliable global energy data provider. It provides information on the global demand (measure in Kilotonnes) for 12 essential raw materials in 2020, necessary for the manufacturing of 14 diverse sustainable energy technologies.

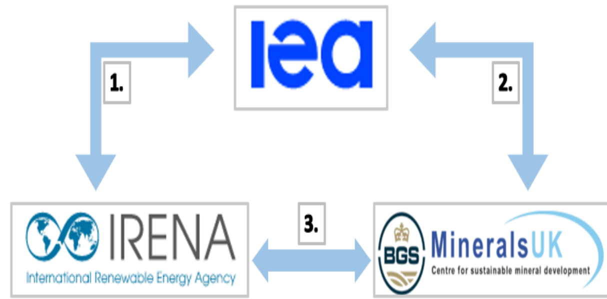

Figure 2: Data join

2.1.2 Energy-related data sources.
For gathering energy-related information, we initially considered Open Power System Data, a platform providing a list of primary data sources helpful for exploring power and energy systems in Europe and worldwide. We found World Resource Institute, DeStatis and Energy Data Service to be particularly interesting, as they were free and reliable data sources. Unfortunately, their data sets did not fully address our research question or had significant amounts of missing data.

We then discovered Entsoe, the association for the cooperation of European transmission system operators responsible for the secure and coordinated operation of Europe's electricity system. It provides information on the energy production for various sustainable and non-sustainable energy technologies in European countries from 2015 to 2023. These data are collected from a yearly to hourly basis and take into account not only the generation of energy but also its transmission and storage within and between countries. While Entsoe was a valid option in terms of data availability, quality, and reliability, we decided to continue our data research to expand our geographic coverage.

Finally, we found *IRENA* to be a reliable and exhaustive source for energy-related information (Figure 2).

This is a prominent global intergovernmental agency for energy transformation, serving as a primary platform for international collaboration and in-depth analysis of technology, innovation, policy, and investment. It provides extensive information on the amount of energy generated by 10 sustainable energy technologies across 180 countries in 2020. This encompasses details on the production, import, export, stock, as well as direct use and transformation into heat or electricity. Additionally, it covers the utilization of energy in residential, industrial, commercial, transportation, and other sectors.

2.2 Data join and selection

The project utilizes the data sets provided by *IRENA*, *IEA*, and *MineralsUK* that have been described above.

Since these data sources differ in focus, dimensions, as well as geographic and temporal scopes, it was necessary to filter those aspects that aligned with our research question and guaranteed a meaningful combination of the data sets. Which data were selected

	Sustainable Energy Technologies (SET)
Variables	Solar photovoltaic, wind turbine, hydroelectric power plant, solid biofuels, geothermal plants, thermal photovoltaic, liquid biofuels, biogas plants, waste-to-energy, pellets
Source	IRENA, IEA
	Sustainable Energy (SE)
Variables	solar energy, wind energy, hydroelectric energy, energy from solid biofuels, geothermal energy, thermal energy, energy from liquid biofuels, energy from biogas plants, energy from waste-to-energy, energy from pellets.
Units	Terajoules (Tj)
Dimensions	Supply, transformation, utilization
Sub-dimensions	Production, import, export, stock, direct use, heat transformation, electricity transformation, residential use, industrial use, commercial use, transportation use
Source	IRENA
Temp. scope	2020
Geo. scope	96 countries
	Critical Raw materials (CRM)
Variables	Chromium, Copper, Manganese, Molybdenum, Nickel, Silver, Zinc
Units	Thousand tonnes (tT)
Dimensions	Production, Import, Export
Source	MineralUK, IEA
Temp. scope	2020 (IEA), 2018 (MineralUK)
Geo. scope	118 countries (MineralUK), global (IEA)

Table 1: Data selection

and how these were joined together is outlined below and summarized in Figure 2 and Table 1.

The data sets from *IRENA* and *IEA* are aligned by their 10 common sustainable energy technologies, which include solar photovoltaic, wind turbine, hydroelectric power plant, solid biofuels, geothermal plants, thermal photovoltaic, liquid biofuels, biogas plants, waste-to-energy, and pellets (Figure 2. connection 1.). *IRENA* primarily concentrates on the production, trade, stock, transformation, and utilization of the sustainable energy generated by these technologies, while *IEA* focuses on their demand for critical raw materials.

The data sets from *IEA* and *MineralsUK* are linked by 7 raw materials, which *IEA* considers essential for the construction of the 10 aforementioned sustainable energy technologies (Figure 2. connection 2.). These critical raw materials comprise Chromium, Copper, Manganese, Molybdenum, Nickel, Silver, and Zinc. While *IEA* emphasizes the technological utilization of these materials, *MineralsUK* focuses on their production, export, and import.

The data sets from *MineralsUK* and *IRENA* are cross-referenced through a total of 96 countries (Figure 1. connection 3.).

Although all three data sets provide yearly data collections, they cover different temporal periods. Therefore, we have decided to focus solely on one year. For *IEA* and *IRENA* we selected the data set from the year 2020, while for *MineralsUK*, we will use the most recent available year, which is 2018.

Summarized, our project's primary variables consist of 10 common sustainable energy technologies from *IRENA* and *IEA* (Table 1, section 2), 10 energy types provided by *IRENA* (Table 1, section 2), and 7 common critical raw materials from *MineralsUK* and *IEA* (Table 1, section 2). The specific dimensions, temporal and geographic coverage are documented in Table 1.

3 APPLICATION SYSTEM AND COMPONENTS

In this section, we will present the fundamental components of the application. Firstly, we will offer a overview of the system design. Subsequently, we will present related works and previous versions that have contributed to the development of this current application. Lastly, we will delve into the graphical user interface, motivating its components, describing its visualizations, and highlighting essential aspects of the underlying code.

3.1 System Design

The program system is comprised of three primary components (Figure 9). The front-end serves as the user interface, enabling access to the application through a web browser and retrieval of necessary data. These data are stored in a database and processed in the back-end. To ensure seamless deployment and consistent execution across various environments, we employ Docker to create a docker image of our application.

3.1.1 *Front-end.*

The client-side of the application is implemented using fundamental web design technologies, including HTML, TypeScript, and CSS. These programming languages allow us to craft the user interface, defining its structure, styling, and behavior. To handle server-side logic, manage libraries, and facilitate smooth client-server communication, we used Node.js, while to create dynamic and responsive user interfaces, we employed the web framework Angular. Additionally, to bring the visualizations to life, we used the D3.js library, a powerful JavaScript toolkit that enables the manipulation and transformation of data into compelling visual representations.

3.1.2 *Back-end.*

The server-side of our application is built using Python. We utilized Flask as the lightweight and versatile web framework, since it can efficiently handle routing, request handling, and template rendering, enabling seamless communication between the front-end and database components.

3.1.3 *Database.*

For efficient storage and management of our data sets, we opted for PostgreSQL, an open-source object-relational database system. To facilitate its administration, we relied on pgAdmin, a comprehensive platform designed for efficient database management and development. The combination of PostgreSQL, pgAdmin, and Docker offered a reliable and streamlined solution for handling data in our full stack architecture.

3.2 Related work

In our earlier work titled *Comparison of Visual Analysis Techniques of the Origin of Raw Materials and Their Supply Chains* conducted during the BA seminar and complemented by subsequent research, we discovered that node-link graphs and maps are extensively employed as visualizations within this domain.

The already mentioned Supply Chain Viewer (SCV) [3] utilizes a force-directed graph to explore material supply chains, effectively investigating aspects like geographic distribution, industry dependency, and production derivatives. However, it does have constraints, including scalability issues, overplotting of symbols or lines, inaccuracies in values, and difficulties in managing multidimensionality. The works from van den Brink et al. [10], Sun et al. [9], Asborno et al. [1], Heidrich et al. [7] also implement node graphs to illustrate material flows and relationships.

The Resource Watch platform and Geological Survey of Sweden (SGU) use interactive symbol, bubble, and choropleth maps to visualize material distribution among major countries, effectively illustrating geographical relationships and spatial patterns. However, they share similar limitations with node-link graphs, including scalability, overplotting, inaccuracies, as well as difficulties in managing multidimensionality and depicting varying region sizes. The platform RMIS, along with the works of Jaffe [8], van den Brink et al. [10], Heidrich et al. [7], Asborno et al. [1], also employ maps to visualize the flow and utilization of critical raw materials.

In addition to node-link graphs and maps, other effective visual techniques have been utilized in platforms and papers to illustrate various aspects of sustainable energy technologies and critical raw materials, including Sankey-diagrams (RMIS, [6], [11]), heat-maps (RMIS), and pie-charts (*IRENA*)

3.3 Previous versions

In the upcoming section, we will showcase our efforts in selecting and implementing the visual approaches mentioned above as the primary visual components of our project. Our choices will be guided by their suitability in visualizing the data and their effectiveness in fulfilling the user tasks. As already mentioned these include the exploration, identification, and analysis of country-based data on sustainable energy technologies, critical raw materials, and energy.

3.3.1 *First version.*

In the project's initial phase, we plan to integrate two essential visual components: a map illustrating energy and material characteristics across various countries and a Sankey-diagram representing the material flow from critical raw material extraction to their utilization in sustainable energy technologies (Figure 3 - red rectangles).

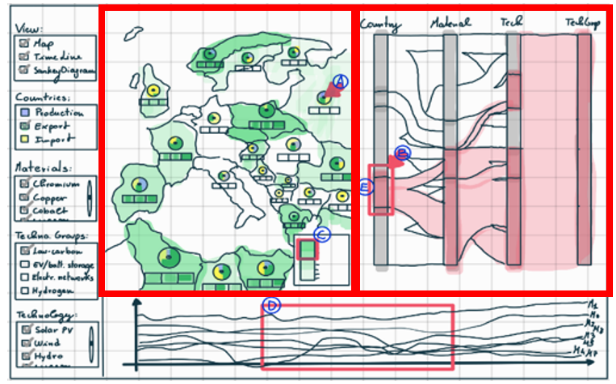

Figure 3: First Version

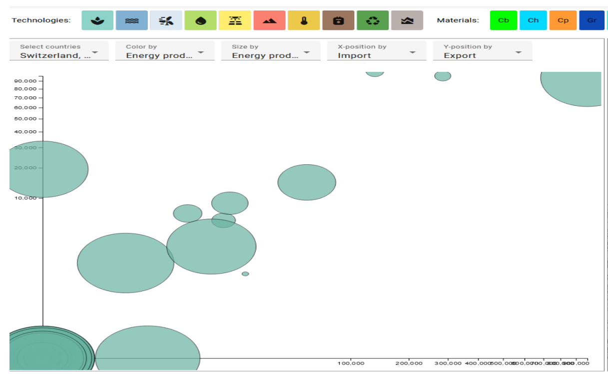

Figure 4: Second version

3.3.2 *Second version.*

However, we discovered that these visual approaches were not the most suitable for our specific goals and data.

As we conducted further research, we acknowledged the potential redundancy that could arise from excessive reliance on maps in this domain. Additionally, attempting to incorporate all dimensions on the map led to symbol overplotting and value inaccuracies.

Similarly, during the development process, we realized the impracticality of implementing a Sankey-diagram. This was due to the diverse variables, dimensions, as well as geographical and temporal scopes of our data (Section 2.2), which made it nearly impossible to create a cohesive representation of the material flows.

Considering these challenges, we investigated other approaches apart from maps and Sankey diagrams to illustrate energy and material characteristics among multiple countries and to depict material flow and usage.

First, we decided to substitute the map with a bubble plot, representing countries as bubbles in a two-dimensional space instead of geographic regions on a map. This allowed us to encode multiple dimensions, reduce the visual clutter, and enhance the visibility of small regions by leveraging the size and position of the bubbles (Figure 4).

3.3.3 *Third version.*

To further enhance the representation of multidimensionality, we

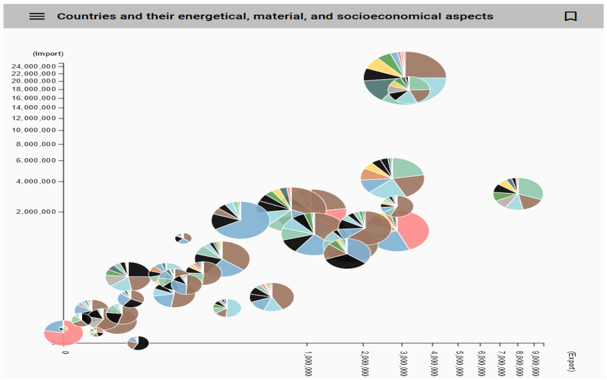

Figure 5: Third version

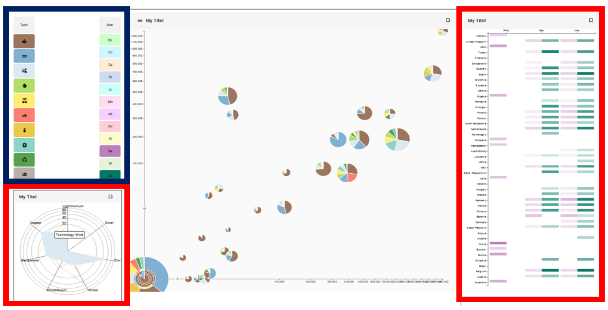

Figure 6: Fourth version

subsequently chose to replace the bubbles with pie-charts (Figure 5).

3.3.4 *Fourth version.*

Second, we opted to replace the Sankey diagram with two visualizations. These allowed us to offer a comprehensive representation of the material trade and utilization, effectively handling the heterogeneity of the data.

The first one is a heat-map, that showcases the production, import, and export of various materials, enabling users to identify trends and patterns across materials, commercial activities, and countries (Figure 6 - red rectangle on the right side).

The second visualization is a spider-chart that illustrates the material utilization for the production of sustainable energy technologies, providing valuable insights into the interconnections between materials and technologies (Figure 6 - red rectangle on the bottom left side).

Additionally, we opted to position the filters, represented by 10 sustainable energy technologies icons and 7 critical raw materials icons, on the top-left side of the application to ensure their constant visibility for users (Figure 6 - blue rectangle on the top left side).

3.3.5 *Fifth version.*

To optimize the utilization of space taken up by the filters and enhance the interpretation of the spider-chart, we introduced an additional visual component resembling a Sankey-diagram. This component connects technology and material icons (Figure 7 - blue rectangle on the top left side).

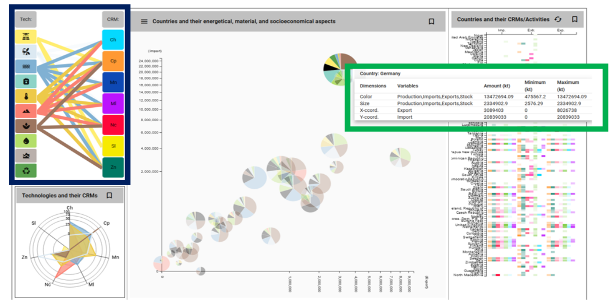

Figure 7: Fifth version

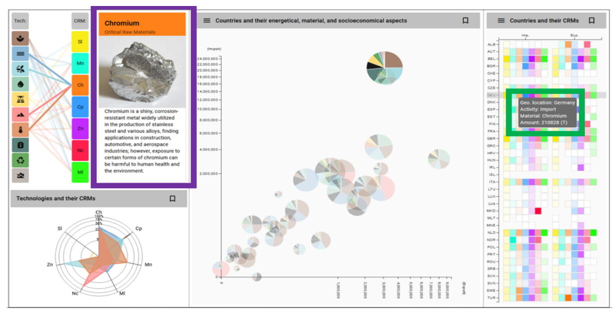

Figure 8: Sixth version

3.3.6 *Sixth version.*

Lastly, we incorporated an information box (Figure 8 - violet rectangle on the top left side) to provide detailed explanations for the visualized data. This approach also prevents overwhelming the tooltip, which used to carry all the information in previous versions (Figure 7 and 8 - green rectangles).

A comprehensive description of the final version of our project will be presented in the next section.

3.4 Graphical user interface

Our project is structured into five components, which we will present in the order that users would typically interact with them (Figure 9). We will emphasize the visual scope, content, and functionalities of each component to provide a comprehensive understanding of their roles within the project.

3.4.1 *Information box.*

First of all, we have the information box (Figure 9 - red component), that provides insights about the application and its elements. This is implemented within the path *frontend> code> scr> app> components> infobox*.

Upon launching the program, this component will introduce the user to the project.

As the user hovers over a visual element within the application, the information box will dynamically display detailed information about the technology, material, energy, or country represented by that specific element. Importantly, this information will remain

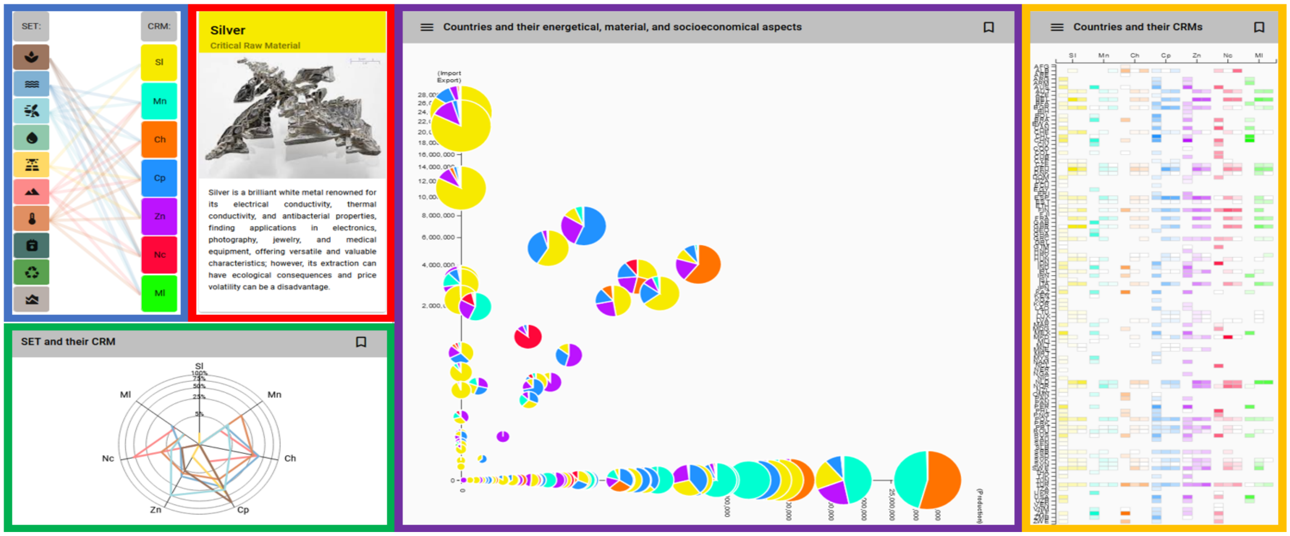

Figure 9: Five Main Components

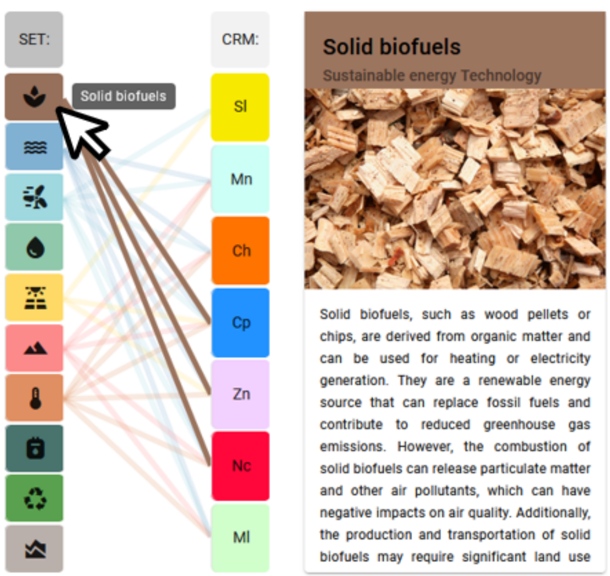

Figure 10: Filters - Hovering over the button representing the sustainable energy technology solid biofuels

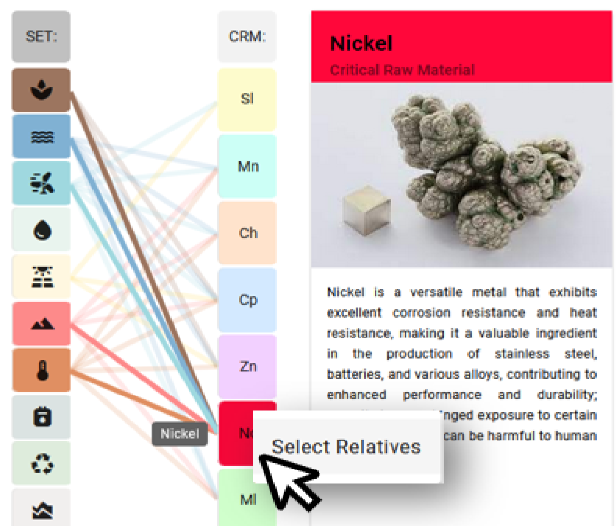

Figure 11: Filters - Filtering the technologies related to the critical raw material Nickel

visible even after the user moves the mouse away from the element, allowing them to freely scroll through the information box or interact with other components.

The specific details presented in this component are further elaborated in the corresponding sections below.

3.4.2 Filters.
This component plays a crucial role in the application, providing users with an overview of the application domain and allowing them to filter sustainable energy technologies and critical raw materials based on their interests (Figure 9 - blue component). It is implemented in the path *frontend* > *code* > *scr* > *app* and serves as the root component within the front-end.

It consists of two lists of buttons, which respectively represent 10 sustainable energy technologies (left column) and 7 critical raw materials (right column) (Figure 10, 11). Besides from functioning as filters, these buttons also inform the users about the technologies and materials we decided to consider in our project based on the available data sets (Section 2, table 1). The arrangement of the buttons corresponds to the most commonly utilized technologies and produced materials. These buttons are thoughtfully designed with colors and icons, carrying semantic meanings to help users associate them with specific technologies (e.g., solar photovoltaic with a yellow pastel color and a photovoltaic panel symbol) or critical raw materials (e.g., Mn for Manganese). To help users distinguish between the two domain groups, different color palettes are used – pastel colors for technology buttons and neon colors for material buttons.

Both lists include a gray button at the top, that serves to deselect or select all underlying buttons, streamlining the filtering process.

Furthermore, the 17 buttons within this component are connected by colored lines, resembling a Sankey-diagram. This visualization effectively highlights which materials are required for the construction of specific sustainable energy technologies and also demonstrates which technologies can be realized from a particular critical raw material. Besides from illustrating the relationships between sustainable energy technologies and critical raw materials, the integration of a Sankey-diagram effectively utilizes the space occupied by the filter buttons.

Users can interact with these buttons in three ways.

When hovering over a button, the related elements are highlighted by slightly darkening the colors of the buttons and lines. Additionally, a tooltip will appear, and the info box will display the scientific name and domain for the hovered technology or material, along with an image and brief description (Figure 10, 11).

Left-clicking enables users to easily deselect or select the corresponding technologies or materials. This selection dynamically updates the visualizations of all other components, allowing users to customize the application according to their preferences and concentrate on specific elements. For partial component independence, a bookmark-shaped button at the top right corner of each component's toolbar can be activated by users to lock the current visualization, preserving the component's visibility even when the main filters are changed.

Right-clicking opens a contextual menu, currently offering the option to filter elements specifically related to the clicked technology or material (Figure 11).

Whenever any element of the other visualization, representing a technology or a material, is hovered over, this component will respond as if the element's button itself had been directly hovered: its color will darken and its connections to the related technologies or materials will highlight (Figure 12, 13).

3.4.3 Spider-chart.

This component was developed to complement and expand upon the functionality of the one described above (Figure 9 - green component). Its code can be found in the project's path *frontend > code > scr > app> components > spidervis.*

It utilizes a spider-chart to visualize the connections between sustainable energy technologies and critical raw materials (Figure 12, 13 - bottom), offering a more precise and detailed method to represent their relationships compared to using simple lines between buttons (Figure 12, 13 - top).

In this visualization, the axes symbolize the materials, while the colored polygon-shaped lines depict the technologies. The colors

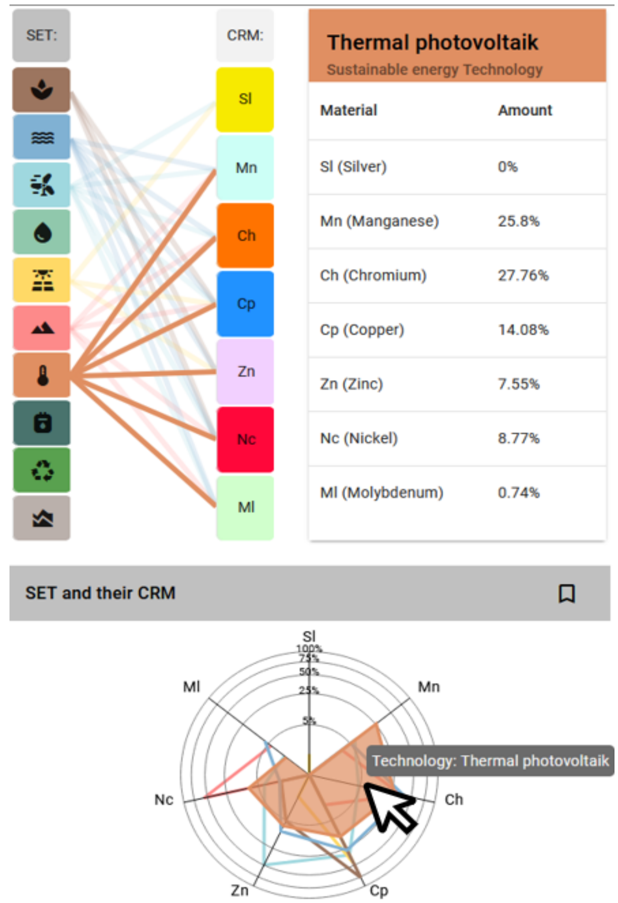

Figure 12: Spider-chart - Hovering over the polygon-shaped line representing the sustainable energy technology Thermal photovoltaik

employed here mirror those used for the filter buttons described above.

The intersection points of the lines with the axes describe the type and percentage of critical raw materials required for the construction of a specific sustainable energy technology. This visual approach facilitates user exploration of the material demand for different sustainable energy technologies and enables easy comparisons in terms of their material criticality.

When hovering over any element in this visualization, a tooltip displaying the specific material or technology name is activated. Specifically, when hovering over the colored polygon-shaped lines, they will be filled with the appropriate color, and the information box will be instantly updated with the name and domain of the hovered sustainable energy technology, along with a table containing the precise share of materials required for its construction (Figure 12). Hovering over the label will fill with the respective colors all the colored polygon-shaped lines representing the technologies dependent on the hovered critical raw material (Figure 13).

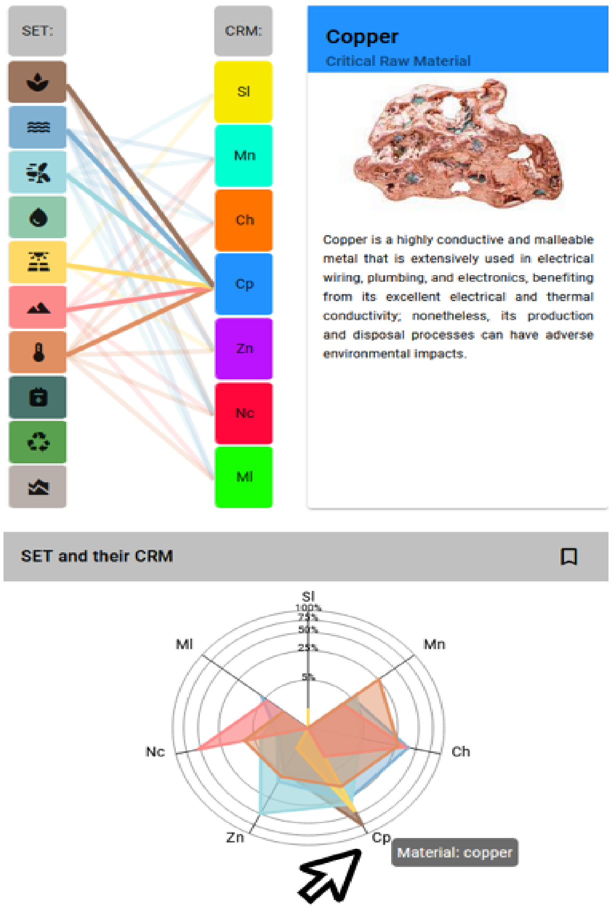

Figure 13: Spider-chart - Hovering over the label representing the critical raw material Copper

Whenever a technology element in the other visualizations is hovered over, this component will mimic the effect of directly hovering over that element's colored polygon-shaped lines, filling them with the correct colors. If the hovered element in the other visualizations represents a critical raw material, the visualization will respond by highlighting the material axis with a grey color (Figure 20).

3.4.4 Pie-chart and pie-plot.

This is the primary visual component of our project, that provide country-based energy and material information (Figure 9 - purple component). It is implemented in the project's path *frontend > code > scr > app > components > pievis*, where two distinct visualizations are coded: pie-chart and pie-plot (Figure 14, 15). Both views incorporate specific filter options, which apply to the sustainable energy technologies and critical raw materials selected with the main filters (Section 3.4.2). By utilizing the filter combinations of these two components, users can gain insights into the desired technology and material dimensions across 96 countries. The dimensions are listed in Table 2.

The first view (*World view*) showcases a basic pie-chart that aggregates data for the desired technology and material dimensions

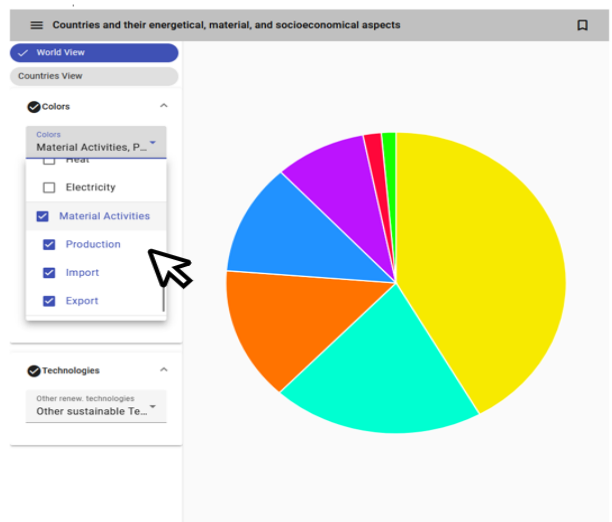

Figure 14: Pie-chart - Selecting the dimensions of interest for the critical raw materials

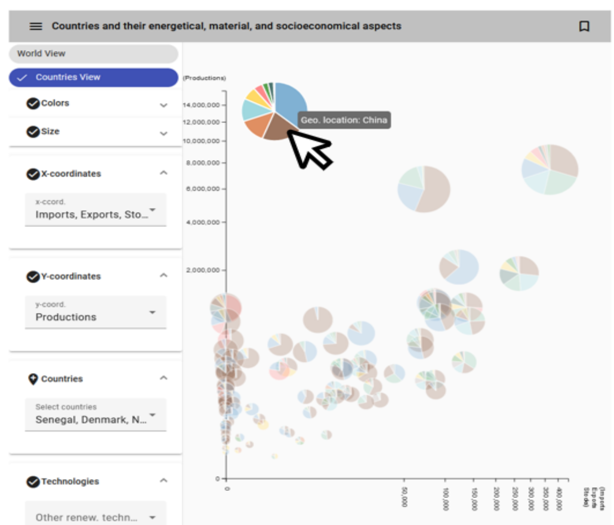

Figure 15: Pie-plot - Hovering over the pie-chart representing the country China

across all 96 countries. Upon program launch, users are presented with a pie-chart, illustrating the global production, import, and export of critical raw materials (Figure 14). This view enables users to identify global trends and patterns related to specific technology or material characteristics of interest.

The second view (*Countries view*) features a bubble plot, where each bubble represents a country and is visualized as a pie-chart. The plot only displays those countries, which are selected in the component's filters and have with size and coordinate values greater than 0. This visualization effectively decodes multiple dimensions using the size, coordinates, and slice angles of the single pie charts, making it ideal for exploring country-based characteristics, trends, and similarities. The colors and order of the slices within the pie charts correspond to those used in the technology and material filter buttons, ensuring consistency.

When a specific slice of the pie chart or a certain bubble of the pie plot is hovered, it will be highlighted, causing the other elements to become opaque (Figure 15).

In the pie chart visualization, a tooltip will appear displaying the full name of the hovered technology or material. Additionally, the information box will update, showing the name, domain, location, amount, and percentage of the energy source or material that has been hovered.

In the pie plot, where the entire pie charts are in focus, a tooltip will appear containing the geographic location represented by the hovered bubble. The information box will present the information of the chosen energy and material dimensions encoded in the size and coordinates of that specific country.

Similarly to the previous visualizations, when the users hover over an element in the other visualizations that represents a critical raw material, sustainable energy source, or country, the corresponding visual component within the pie-chart or the pie-plot will be highlighted as if directly hovered over (Figure 20).

3.4.5 *Heat-map.*

This component focuses on the production, export, and import of critical raw materials across 118 countries. Like the previous component, it presents two distinct views that are implemented in the project's path *frontend > code > scr > app > components > heatmap.*

In both views, the component utilizes a heat-map with colored rectangles representing the quantities of material produced, imported, and exported globally. The rectangle colors correspond to those used in the filter buttons to represent the critical raw materials. The hues encode the proportional amount of material produced and traded across the countries, with darker colors indicating larger amounts.

The y-axis represents the geographic locations of 116 countries actively producing or trading at least one of the selected critical raw materials. The component offers user-friendly filters for easily selecting specific countries of interest. These are listed in the filters and the visualization in alphabetical order, making it easier for users to locate them.

The x-axis considers the critical raw materials selected with the main filter buttons or the commercial activities chosen in this component's filters. This varies according to the chosen view.

In the first view (*Materials view*), the x-axis presents the critical raw materials, dividing the visualization into sections corresponding to the selected critical raw materials, each including the chosen commercial activities (Figure 16). This enables precise comparisons between geographic locations and commercial activities associated with specific critical raw materials.

In the other view (*Activities view*), the x-axis focuses on the countries' activities, subdividing the visualization into sections corresponding to the chosen industrial activities, each including the selected critical raw materials (Figure 17). As already mentioned, the users can freely choose these activities in the component's

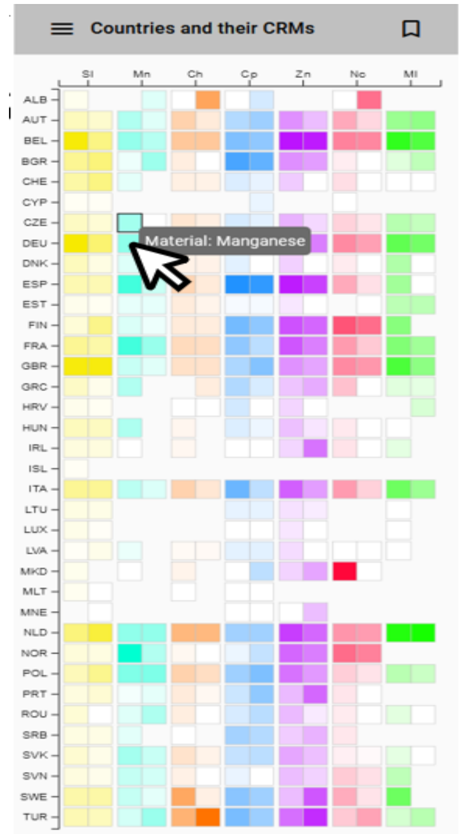

Figure 16: Heat-map - Hovering over the rectangles representing the imported critical raw material Manganese in Czech Republic

filters. This view facilitates comparisons between countries and materials falling under the same trade activity.

Hovering over any element in these two views activates a tooltip displaying the full name of the country, material, or activity it represents. When users hover over the rectangles, they are highlighted with a black border, and the information box is updated with the name, geographic location, industrial activity, and material amount related to the hovered critical raw material. Additionally, when countries in the y-axis and current materials or activities in the x-axis are hovered over, the corresponding sections will be highlighted with a grey color (Figure 17).

Whenever any element of the other visualizations representing a country or material is hovered over, this component will respond as if the visual component of this element itself had been directly hovered: its section will be highlighted in a grey color (Figure 20).

3.5 Code characteristics

In the following section, we will delve into the technical aspects of our project, showcasing the scope, structure, interactions, and

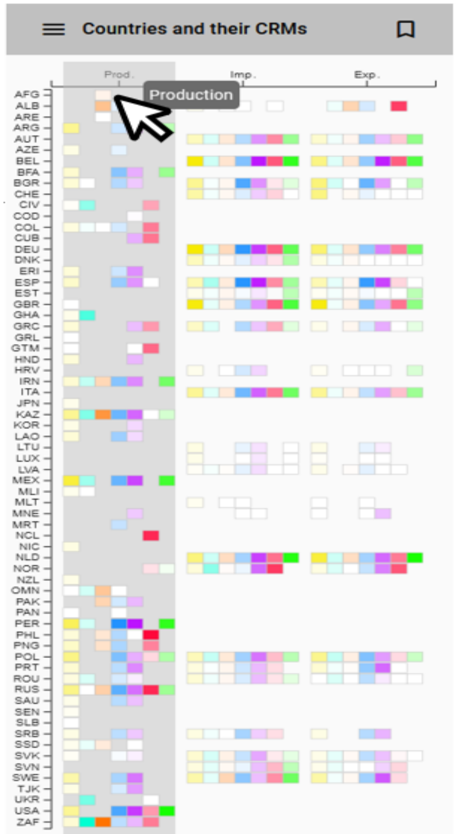

Figure 17: Heat-map - Hovering over the production section including all seven critical raw materials

functions related to the main code. While this technical documentation may not be crucial for grasping the project's overall concept, it serves as a robust foundation for developing future features and components in our upcoming works.

Assuming that Docker is installed on the PC, this project can be locally launched by executing the command "docker-compose up −−build" in the console within the project's directory. This will run the file *Docker-compose.yml* (Figure 18), which is necessary to set up the services (front-end, back-end, and database), extend the necessary base images (node, python, kartoza/postgis), and import the CSV files into the PostgreSQL database.

3.5.1 Front-end.

This is the most elaborated and interconnected part of the project. It contains essential files and folders, including the *Dockerfile* responsible for extending the node base image, installing necessary modules, and running the server (Figure 18, 19). Located in the path *frontend>code>scr>app*, there are five files and three folders.

The two files *app.module.ts* and *app-routing.module.ts* are used for configuring the Angular application's modules, components, services, and routing functionalities.

App.component.html, *app.component.css*, *app.component.ts* are three files associated with the Angular component *AppComponent*, which plays a crucial role as the entry point for the entire Angular application (Figure 18, 19).

This component is mainly responsible for visualizing the filter buttons and their connections (Figure 9 - blue component, section 3.4.2).

Additionally, the *AppComponent* acts as a central connection point among the other four Angular components: *pievis*, *spidervis*, *heatmap*, *infobox*. It transmits information about the selected sustainable energy technologies and critical raw materials to these components, which use them as parameters for HTTP POST requests to the back-end endpoints. It then shares the retrieved data as well as other important local variables between these four components, which utilize them to synchronize and complete their visualizations (Figure 19).

In the *components* folder, are located these four Angular components, including their html, css and TypeScript files.

The *infobox* component differs from the others as it solely receives information, specifically from the other components through the *AppComponent* (Figure 19). This data pertains to the hovered element of other visualizations, which is then combined and presented in the information box in the form of text or a table (Figure 9 - red component, section 3.4.1).

The other three components communicate bidirectionally with and through the *AppComponent*. The components *spidervis*, *pievis*, and *heatmap* are respectively responsible for visualizing the spider-chart (Figure 9 - green component, section 3.4.3), the pie-chart and pie-plot (Figure 9 - violet component, section 3.4.4), and the heat-map (Figure 9 - yellow component, section 3.4.5). Each component features an Angular Material toolbar containing the title and interactive options of the respective visualization, which is implemented in a <div> directly under the toolbar. All visualizations are implemented using *Scalable Vector Graphics* (SVG) - an XML-based vector graphics format to draw various shapes and create powerful and flexible visualizations. In the *pievis* and *heatmap* components, the SVG is placed within an Angular Material drawer-container to organize filter options in the drawer and the corresponding visualizations in the content section. These visualizations can to automatically adjust their size based on the available screen space. This is achieved using the functions *onHeatMapResize()*, *onSpiderDiagrResize()*, and *onPieResize()*, which recreate the SVG and update the visualizations according to the current size of the <div> in which they are embedded.

Each TypeScript file in these components includes the following functions: *ngOnChanges()* to handle changes in filtered technologies and materials from the *AppComponent*, *blockVis()* to block visualizations independently from changed filters, *callSQLfunk()* to call functions in the file *backend.service.ts* and fetch necessary data from the backend, *createSVG()* to create the SVG, as well as other functions, such as *createSankey()*, *createSpiderDiagr()*, *createPieChart()*, *createPiePlot()*, *createHeatMap()*, to create respective visualizations within the SVG, which are executed upon filter updates.

All Angular components in our project utilize models and classes containing information on countries, technologies, materials, and

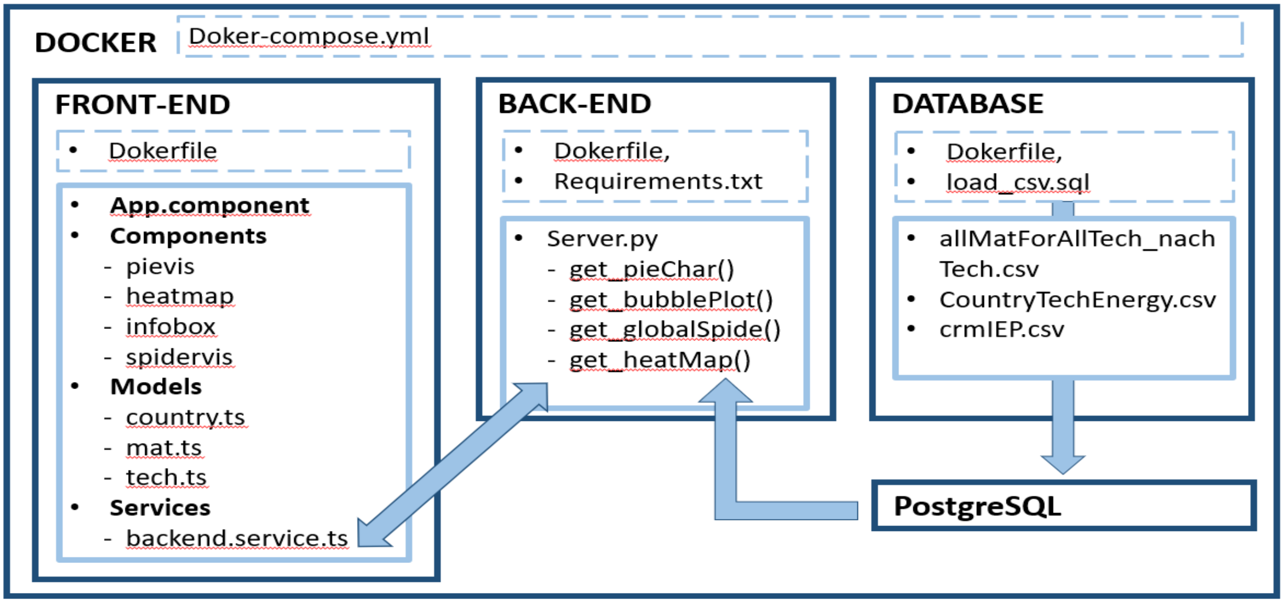

Figure 18: System components

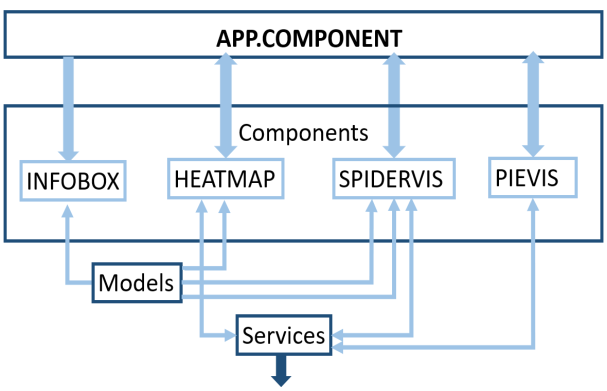

Figure 19: Front-end components

energy sources provided in our data sets. These are stored in the *models* folder and ensure structured storage and reusability of common data across the various Angular components described above (Figure 18, 19). The file *country.ts* contains two *Enums*, one for the 96 countries used for the pie-chart and pie-plot visualizations of the *pieVis* component, and another for the 118 countries used in the heat-map visualization of the *heatmap* component. The files *mat.ts* and *tech.ts* store *Enums* with details like dimensions, colors, abbreviations, scientific names, descriptions, and image paths for the 10 sustainable energy technologies and 7 critical raw materials.

The *services* folder contains the file *backend.service.ts*, responsible for facilitating communication with the backend. This separation of concerns enhances code organization, maintainability, and reusability in the front-end codebase (Figure 18, 19). It incorporates various functions such as *fetchpiePlot()*, *fetchpieChart()*, *fetchHeatMap()*, and *fetchSpiderDiagr()*, which are responsible for sending HTTP requests with parameters for database queries to the appropriate server endpoint and receiving the relevant data required to visualize it using the corresponding visual approach. The file also handles errors and asynchronous operations using RxJS Observables.

In the path *frontend>code>scr>assets* are stored the images displayed in the *infoBox* component when hovering over the technology or material icons.

3.5.2 Back-end.

This component comprises a *Dockerfile* and a *requirments.sql* file, essential for extending the *Python* image and other necessary requirements (Figure 18).

The central file *server.py* in the path *backend>code* contains all the crucial routes for handling POST requests from the front-end. Each route corresponds to a specific function that is responsible for extracting data sent as the body of the request from the front-end (*data = request.get-json()*), executing the required database queries (*cursor.execute(query)*), and returning the expected data for creating the desired visualization to the front-end (*return jsonify(output), 200*). There are in total four functions responsible for collecting data to visualize the user-selected information in the web-browser: *get-pieChart()*, *get-bubblePlot()*, *get-globalSpider*, *get-heatMap()* (Figure 18). The back-end also include the same models and classes as the front-end.

3.5.3 Database.

This component comprises a *Dockerfile* and a *load-csv.sql* file, essential for extending the *kartoza/postgis* image and importing the CSV files into the PostgreSQL database (Figure 18).

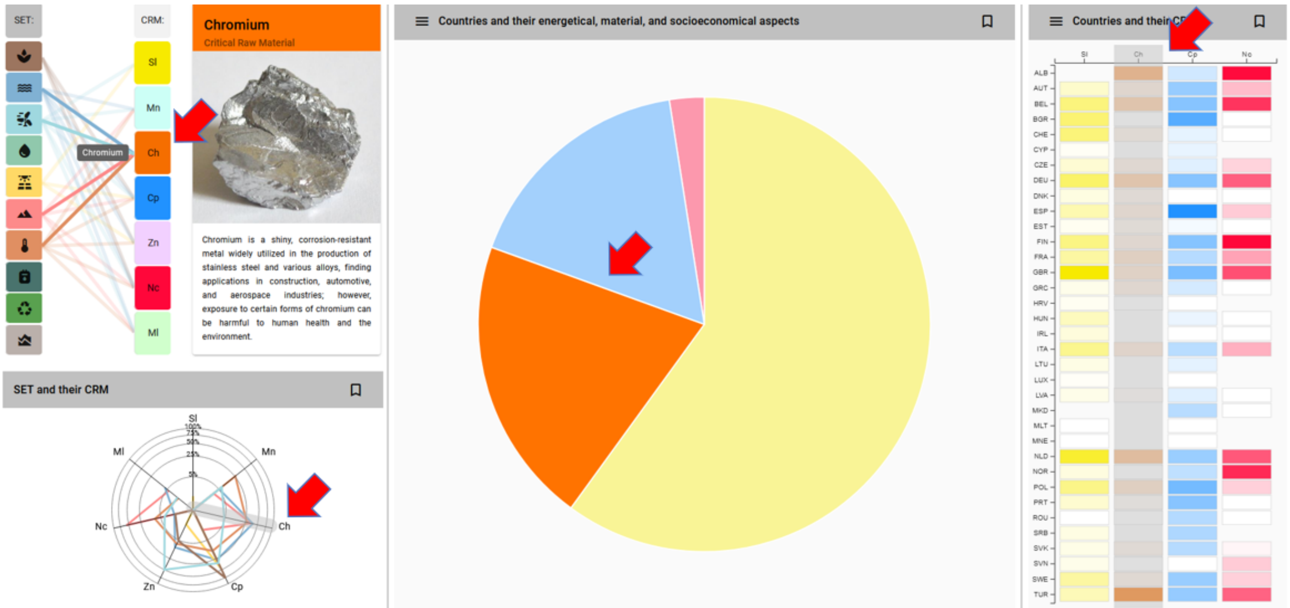

Figure 20: Highlighting elements representing the same critical raw material Chromium

It contains approximately 20 data sets, which we collected from the data sources *IRENA*, *IEA*, and *MineralsUK*. These data sets underwent both automated and manual preprocessing to create three main CSV files: *allMatsForAllTech-nachTech.csv*, containing information from *IEA* on the material demand for each sustainable energy technology; *countryTechEnergy.csv*, containing country-based energy-related information from *IRENA*; and *crmIEP.csv*, containing country-based material-related information from *MineralsUK*. Upon executing the mentioned Docker command, these data sets were imported into the PostgreSQL database, enabling the back-end to access the necessary information from the database (Figure 18).

4 INTERACTIVE WORKFLOW

In the next section, we contextualize the system components by showcasing five user-tasks and illustrating how these can be fulfilled through a sample use-case scenario.

4.1 User-tasks

As already mentioned, this application was designed to visualize various global and country-based aspects of the main sustainable energy technologies. These aspects include the production, trade, and utilization of critical raw materials demanded for the construction of these technologies as well as the production, trade, storage, utilization, and transformation of the sustainable energy derived from them.

By employing the visualizations outlined in the preceding section, the users can complete the following tasks:

T1*: Analyze the characteristics and relationships of sustainable energy technologies and their critical raw materials.*
For example: What are the main sustainable energy technologies, and what are their key characteristics? Which critical raw materials are required for the construction of such sustainable energy technologies? Which critical raw materials are demanded for a specific technology? Which sustainable energy technologies rely on specific materials?

T2*: Compare the material criticality of sustainable energy technologies, as well as the production potential, commercial suitability, usage tendency, and transformation possibility of the energy produced by them.*
For example: Which sustainable energy technology uses the most and least materials? Which sustainable energy technology relies the most and least on a specific material? Which technologies share similarities in the number, type, and amount of critical raw materials they demand? Which sustainable energy technology produce most energy? Which technologies are more or less suitable for specific commercial activities?

T3*: Explore the global and regional characteristics of energy production, trade, transformation, and utilization, as well as the global and regional characteristics of material production and trade.*
For example: What types of sustainable energy technologies are utilized worldwide for energy production, and to what extent are they employed? How much do a specific critical raw material contribute to the worldwide material import?

T4*: Identify possible correlations and patterns between energy and/or material dimensions.*
For example: Is there a correlation between material production and trade across countries? Is there a relationship between the sustainable energy technology most used for energy production in a country and the critical materials this country produce or trade?

T5*: Identify geographical patterns based on technology and material characteristics of the depicted countries.*
For example: Can geographic groups be identified in relation to a

specific energy or material aspect? Do some countries behave as outliers? Is there a relationship between certain technology and material characteristics and known geographic, economic, or social features of the depicted countries?

4.2 User-interactivity

Before demonstrating the functions of the application in a use-case scenario, we will provide a summary of its interactivity, with a particular focus on the filtering and hovering options.

The primary filter options are located in the left-top corner and represent the 10 sustainable energy technologies and 7 critical raw materials based on available data sets (Table 1, section 2). These apply to each visualization of the five visual components described above (Section 3.4, figure 9). The components representing the pie chart, pie plot, and heat map provide additional filters, allowing better control over the technology, material, or energy dimensions illustrated within each component.

Each component includes a button to lock the current visualization, preserving the components' independence and enabling users to maintain visualizations of interest while further interacting with the application.

To enhance users' ability to grasp the relationships between the data sets and the visualizations, as well as to identify patterns across component borders, we implemented in our application synchronized highlighting of all visual elements representing to the currently hovered sustainable energy technology, critical raw material, sustainable energy source, or country.

An example is presented in Figure 20, where the filter button representing Chromium is hovered over. Automatically, the lines in the Sankey-diagram connecting this material to the dependent sustainable energy technologies and the slice of the pie-chart representing this material are darkened in the same orange color as the filetr button. Simultaneously, the axis within the spider-chart and the vertical section within the heat-map representing this material are highlighted in grey.

4.3 Use-case scenario

Let's consider a user residing in Germany who has a keen interest in photovoltaic technologies, since Germany has made in the last years significant investments in terms of financial resources and policies towards promoting and advancing this particular sustainable energy technology.

The user will start by exploring the filters located at the top left of the application to understand which sustainable energy technologies are considered in this application (***T1***) (Figure 21). Thanks to the semantically meaningful colors and icons on the filter buttons, as well as the information displayed in the tooltip and infobox, the user can effortlessly identify two sustainable energy technologies of interest: solar photovoltaic and thermal photovoltaic (***T1***). To obtain more details about their characteristics, the user can refer to the descriptions provided in the infobox (***T1***).

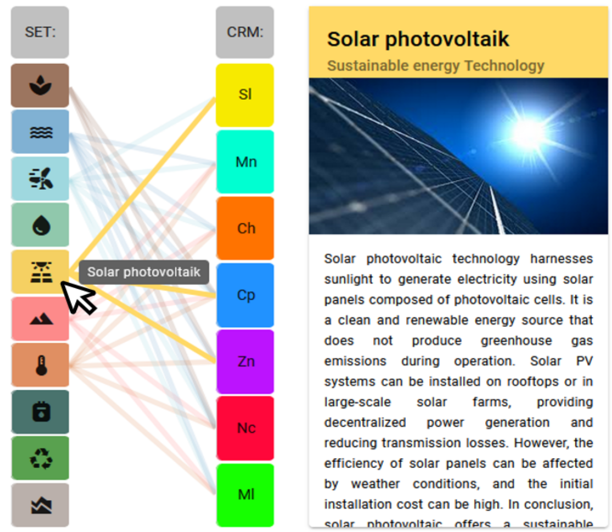

Figure 21: Identifying solar photovoltaic technologies as element of interest and exploring its characteristics

By hovering over the corresponding filter buttons (Figure 21) and spider-chart lines (Figure 22), the user can identify the critical raw materials essential for constructing solar photovoltaic and thermal photovoltaic technologies (***T1***). By comparing the lines connecting the filter buttons (Figure 21, 22 - top) or intersecting the axes of the spider-chart (Figure 22 - bottom), the user can assess the material criticality of these two technologies. For example, the user may observe unaspected differences between solar and thermal photovoltaic technologies, especially in terms of the type, number, and amount of materials they require (***T2***). For more detailed information, the user can refer to the tables provided in the infobox (***T2***).

After shifting the attention to the central component and modifying the filters of the pie-chart, the user have the capability to examine global trends related to the production, trade, transformation, and utilization of the sustainable energy technologies, including the two photovoltaic technologies (***T3***). For instance, the user may discover that solar and thermal photovoltaic technologies generate a similar amount of energy. According to the tabls in the information box this is around 4% (***T3***).

By switching the central component's view from *World view* to *Countries view*, the user gains the ability to identify and analyze potential energy, material, or geographic patterns and interdependences (***T4, T5***).

For example, the user can explore the country-based energy transformation of all sustainable energy technologies (Figure 24) and the country-based industrial activity of Copper and Zinc, necessary materials for both photovoltaic technologies (Figure 25). In both pie-plots, illustrated in figure 24 and 25, the user may observe that there are no correlations (***T4***), either between the amount of energy (measured in Terajoules (Tj)) being transformed into heat (Figure 24, x-axis) and energy (Figure 24, y-axis) or between the amount of materials (measured in Kilotonne (Kt)) being traded (Figure 25, x-axis) and produced (Figure 25, y-axis). However, the

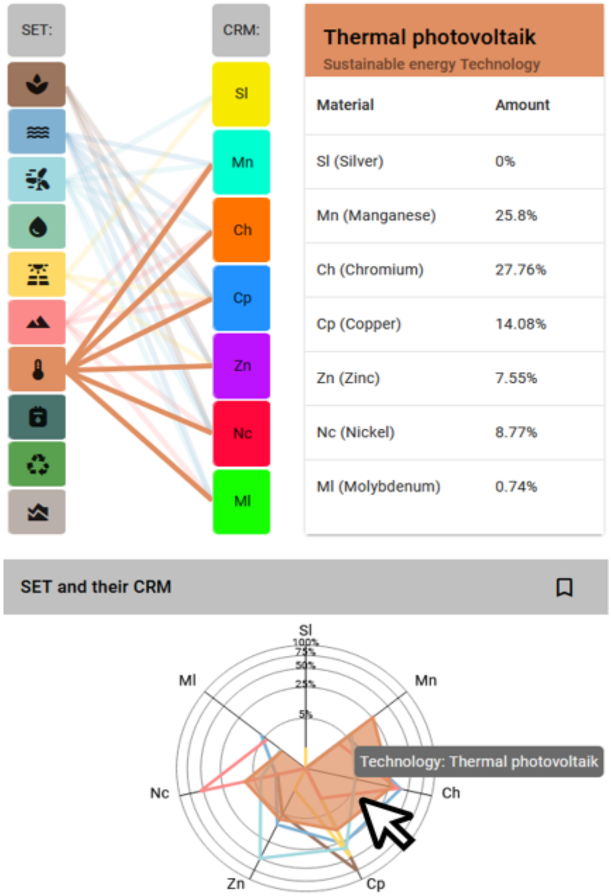

Figure 22: Identifying type, number, and amount of critical raw materials demanded for thermal photovoltaic technologies

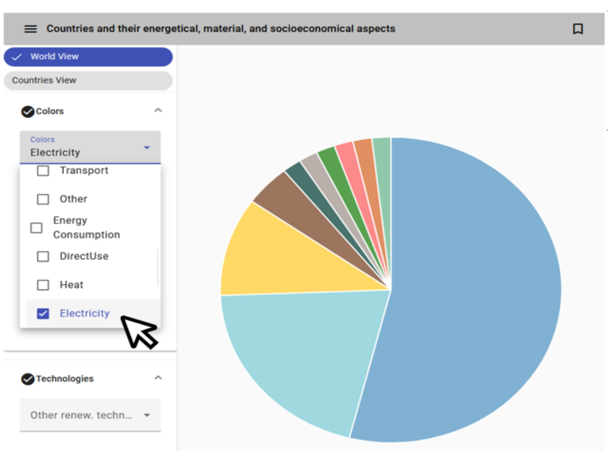

Figure 23: Analyze worldwide trends in the transformation of sustainable energy technologies for energy generation

Figure 24: Identifying and analyzing energy and geographic patterns in the transformation of sustainable energy into electricity

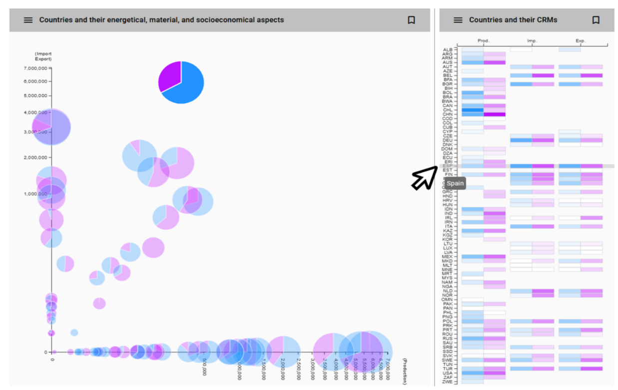

Figure 25: Identifying and analyzing material and geographic patterns in the production and trade of Copper and Zinc

user may identify some geographic patterns (*T5*). For example, the user may notice that the countries aligned on the y-axis of Figure 24, such as Zambia, Peru, South Africa, are known to be warm countries, while those in the right top extremity of the plot, such as Iceland, Norway, Ireland, are known to be subjected to cold temperatures. This may suggest a positive relationship between the known climatic characteristics of the countries and the amount of energy they consume for heating (*T5*). Similarly, two groups of countries can be identified in Figure 25, where geographically extensive and economically weaker nations like China, USA, Mexico, Peru, Namibia, predominantly produce critical raw materials, while so-called industrial countries primarily engage in their import and export (*T5*). The heat-map further confirms this observation, making the distinction in activity tendencies among countries even more evident (*T5*). The user may also notice that are some outliers, such as Spain (Figure 25, hovered element), which take part in all industrial activities (*T5*).

5 DRAWBACKS

Our application is currently functional and, as demonstrated in the previous section, it fulfills the main user tasks. However, there are still some data and visualization-related drawbacks that may need to be addressed before and while working on the Bachelor thesis.

As described in section 2, the data collection process posed significant challenges for our project, both in terms of time consumption and technical complexities.

Despite managing to collect the necessary data for our research question, the underlying data sources suffer from two main issues: heterogeneity and poor quality. The data sets vary in focus, dimensions, as well as geographical and temporal scope, which makes it difficult to find and implement visualizations capable of handling these differences effectively. Furthermore, the data sources, especially *IRENA*, exhibit numerous inconsistencies and missing values, which complicate the task of conducting precise and comprehensive analysis.

As stated in the beginning of section 3, our project underwent several changes to discover and finally implement the most suitable visual approaches for visualizing multiple energy and material aspects related to sustainable energy technologies.

However, some drawbacks emerged during the initial iteration of evaluations. The visualizations could offer more user-interactions, despite tooltips, or filtering, blocking, and hovering options (Section 4.2). Similarly, the information boxes may benefit from including more relevant details about the hovered element of the visualizations. The most significant issue identified in the first evaluation pertains to the pie-plot. Specifically, the pie-charts representing countries suffer from overplotting and varying sizes. Moreover, the filters are challenging to understand and select in a meaningful way, which consequently hampers the creation and interpretation of the pie-plot visualization.

6 FUTURE WORK

Currently, we are in the evaluation phase of our application. The insights we will gain from this phase will play a crucial role in shaping future works and the Bachelor's thesis. While awaiting user feedback, we could proactively address the identified drawbacks through data and visualization enhancements.

With regard to our database, we could incorporate two additional data sets.

The first data set, sourced from the *IRENA* website, offers more comprehensive information on the relationship between technologies and materials compared to our current one. By replacing the current *IRENA* data set with this new one, we might also need to include other data sets related to country-based production and trade of critical raw materials from the *MineralsUK* platform. These changes will significantly improve the data quality and precision with relative small effort.

The second data set, obtained from OECD, contains country-based geographical, social, political, and economic data. Incorporating this information will enable us to expand the pattern and correlation analyses of our application beyond the material, technology, and energy domains.

For our visualizations, we could improve the user-interactivity, by introducing features like zoom and brush for all visual components.

Furthermore, we could update the filters of the pie-plot visualization, which received substantial criticism during our initial evaluation, in order to improve the user's understanding of the filters and interpretation of the results.

If time allows, we could offer users the ability to arrange visualization elements with greater freedom, for example through a cluster algorithm, that group elements in ways beyond the conventional numerical or alphabetical order as used so far in the pie-plot and heat-map.

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