Interactive Visualization of Energy System

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***Abstract*—Energy systems are under pressure to transform in order to address concerns about climate change. The modeling and visualization of energy systems can play an important role in communicating the costs, benefits and tradeoffs of energy systems choices. We introduce a visualization tool that provides an interface for exploring time-varying, multi-attribute and spatial properties of a particular energy system. The tool integrates several visualization techniques to facilitate exploration of a particular energy system. These techniques include flow diagram representation to show energy flow, 3D interaction with flow diagrams for expanding viewable data attributes such as emissions and an interactive map integrated with flow diagrams for simultaneous exploration of spatial and abstract information. We also perform level of detail exploration on flow diagrams and use smooth animation across the visualizations to represent time-varying data. As a means of preliminary evaluation, we have included feedback on this tool from our energy system collaborators.**

***Keywords*-Energy system; visualization; flow; sankey diagram; time-varying; spatial; animation;**

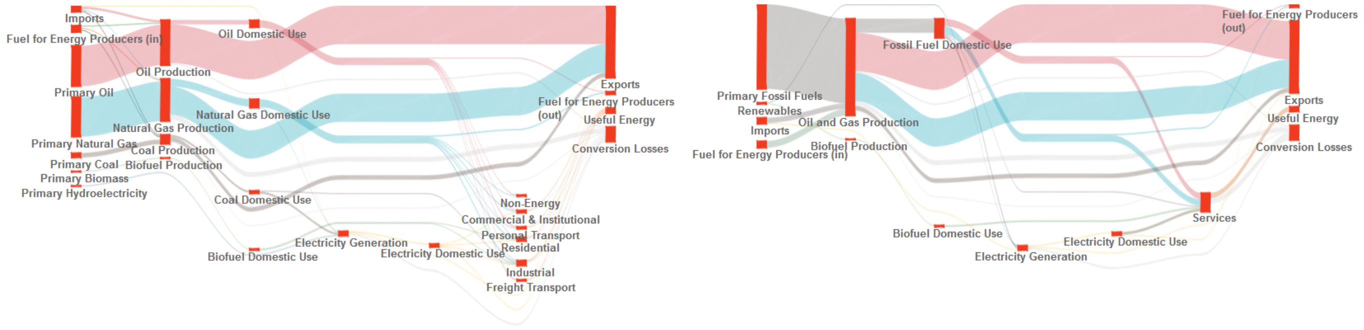
I. INTRODUCTION

The energy systems of developed nations have fueled a very high quality of life, delivering luxuries that would be the envy of all previous generations. Such systems include all stages in energy flow from its recovery from nature, through the creation of energy currencies (gasoline, electricity etc.) to the delivery of energy services to meet societal demand. Today the global scale of climate changing greenhouse gas (GHG) and its frightening environmental and economic implications have focused attention on the need to transform our energy systems. Developing policies and investment strategies designed to make energy systems sustainable requires an understanding of the nature of our existing energy systems.

Sankey diagrams are a type of flow diagram in which flow widths represent flow quantity. Early examples of using Sankey diagrams on maps can be found in Minard's illustrations [1]. These diagrams are commonly used to show the magnitude of energy flows from resources, through commodities to services as in International Energy Agency's website [2]. They provide a top-down perspective on energy systems and make it possible to identify major features, inconsistencies or questionable aspects of the data that require closer and critical analysis.

Despite the usefulness of Sankey diagrams, the structure of an energy system can be too complex to be fully captured in a single diagram. Complex systems can require several visualizations applied together to show all properties in a dataset [3]. Figure 1a shows a Sankey diagram generated by our system with many details. Figure 1b has reduced the complexity by reducing the number of nodes in the diagram. The energy system data consists of spatial, time-varying and multi-attribute features as well as flow information which requires more advanced visualizations to capture all of this information. In this paper we introduce an interactive tool for visualization of Canadian energy system which handles the complexity of this dataset using linked views. The main component of our visualization system is interactive Sankey diagrams. To address the complexity of the energy systems, we support a level-of-detail exploration of the diagram using hierarchical structure for the data. We also take advantage of an interactive map to show spatial information and explore regional Sankey diagrams. To support viewing GHG emissions, we display them as simple bar charts perpendicular to the Sankey diagram's plane. We make clear the association of these attributes and conventional Sankey by using a smooth animation for changing view. We use smooth animation for other aspects of this visualization system as well, including the temporal change and drilling up and down in level-of-detail. The contributions of this paper include:

- a detailed data abstraction and task analysis of energy system and proposing visualization techniques accordingly;
- interactive visualization of Sankey diagrams across several years by smoothly animating the changes in each time step;
- level-of-detail interaction with Sankey diagrams using a hierarchical data structure;
- using an interactive map to show regional Sankey diagrams and to connect spatial information with abstract data;
- visualization of multiple attributes on top of a Sankey diagrams by changing view of the diagram using smooth animation.



(a)

(b)

Figure 1: Visualization of Canadian energy system using level-of-detail exploration. (a) A Sankey diagram with many details. (b) A simplified Sankey diagram.

The remainder of this paper is organized as follows. Section II presents a background on Energy system and tasks based on which we designed our system. Related work follows in Section III. We discuss data abstraction and required data structures in Section V. We describe our design choices for different aspects of energy system dataset in Section V. A discussion of our design decisions and expert feedbacks is also provided in VI. This paper ends in VIII with a conclusion and ideas for future work.

II. Energy System Background

Energy systems encompass the generation and conversion technologies as well as the distribution network which provide energy services (mobility, comfort, light, nutrition, industrial products, etc) from the energy sources that nature provides. Examples of energy sources include the fossil fuels (coal, oil and gas), uranium and renewables (hydropower, biomass, wind, solar). These energy sources are converted into commodities or currencies (e.g., gasoline, diesel, electricity, wood pellets, etc) that can be moved to where the energy is needed to be converted into a service. In this project we used data from the Canadian Energy Systems Simulation (CanESS) model [4]. CanESS draws on historical data from a range of government sources, combines it with detailed stock and flow data on energy conversion technologies to create an integrated model of energy flows and GHG emissions by Canadian province for the period 1978 to 2010. This historical model is then used to project the nature of future energy systems (esp. energy flows and GHG emissions) based on assumptions about population and GDP growth, energy sources, conversion technologies and service demand.

Some of the elements that form energy systems are the energy flow inside a region, production levels for energy sources, trade of energy across regions and also other attributes such as amount of green house gas (GHG) emissions produced through out the process of energy generation to delivery. CANESS provides energy system data for each province of Canada as well as trades, i.e. imports and exports, between provinces and internationally.

Task analysis: Our project is motivated by the need of our energy specialist collaborators for more sophisticated visualizations that can be used both for public awareness and for decision makers. While Sankey diagrams have been widely used in visualizing energy systems, they can be criticized in different aspects. On one hand Sankey diagrams are too simple as they are only a snapshots of energy flows in time. On the other, a Sankey diagram could be too complex when populated with highly detailed information that makes it difficult to see important aspects of the energy system being represented. Besides, other information such as GHG emissions can not be simply added to a Sankey diagram as it increases its visual complexity.

Environmental impacts are the major motivation for studying energy systems and research attempts have been made towards providing feasible solutions to reduce the impacts such as replacing renewables for fossil fuels. Specifically, GHG emissions are one of the main components of interest in analysis of energy systems. Other impacts include but are not limited to amount of land and water usage. A more advanced visualization than traditional Sankey diagrams can facilitate incorporating these features into the visualization.

In summary, based on the user requirements mentioned above and the properties of the CANESS dataset, we detected the following tasks:

- having an insight on temporal changes in the energy system. This feature is specially important when different perspectives on past, present and possible future energy systems are viewed simultaneously. Such insight is especially valuable for decision makers as they consider different policy and investment strategies;
- viewing Sankey diagrams at different levels of detail for reducing or increasing the visual complexity at need;
- visualizing GHG emissions as a major component of studying energy systems as well as spatial information i.e., imports and exports.

III. RELATED WORK

Our work addresses the challenge of designing a visualization tool intended for energy systems; this draws upon research in several related domains. In this section we review several related domains to this research including: visualization of flow, visualization of time and space and linked visualizations.

A. *Visualization of flow*

Flow shows the amount of change from one state or element to another. Visualization of flow appears in many application areas. A previous system which directly addresses visualization of energy system is the work by Riehmann et al [5]. In this work they address visualization of energy system of a city using interactive Sankey diagrams. The other recent examples of using flow diagrams is Outflow system [6]. In this system, temporal event sequences are visualized using edges between time steps to show progression of an event.

The other examples most related to visualization of flow fall under research area of categorical data visualization. Parallel sets [7] is a technique to visualize categorical data and quantities which pass between classes of data and is an extension to parallel coordinates technique [8]. An example system which uses parallel sets to show people's movement information from one group to another, is the work done by von Landesberger et al. [9]. In their approach, parallel sets are used to show change in classes of data over time.

The other class of research related to flow, focuses on visualization of flow on a map. This representation is called flow map. Phan et al. [10] initially introduced flow maps and presented algorithms for optimizing layout of flow maps and reducing visual clutter. We use a basic flow map representation to show regional interactions on a map.

B. *Time-varying data visualization*

There is a vast literature on visualization of time-varying data [11], [12]. Various techniques to visualize time, focus on either static representation of all time steps in 2D or 3D space or dynamic visualization using animation [13]. Small multiples [14] is a technique which puts together different variations of a single visualization distinguished by time or other features. This technique however limits the number of viewable time steps due to lack of screen space. Kothur et al. [15] suggest a clustering technique to reduce the number of maps required to represent data.

Animation is also used in many applications to show temporal changes. Arguments exist around effectiveness of animation to visualize trends [16], [17], however, animation has proved successful for presentation and viewing results of analysis [17], [13]. Gapminder [18] is an example of a successful use of animation in information visualization.

C. *Linked visualization*

Our system presents a combination of visualization techniques to facilitate exploration of different features of an energy system. Several other systems have been previously proposed to support spatio-temporal and multivariate features of a dataset. An example system is VIS-STAMP [19] which provides a framework for a comprehensive visualization of spatio-temporal multi-attribute datasets. They conceptually represent such datasets as a cube defined by three components: geography, attributes and time and suggest linked visualizations to support each of these components. Graphdice [20] is another example system which uses linked visualization for multi-attribute social networks. VisLink [21] is a visualization tool which addresses linking several visualizations through edges that connect same entities across several visualizations.

IV. DATA ABSTRACTION

In this section we present a detailed data abstraction of the problem domain to clarify the underlying data structure required to model an energy system. As discussed in Section II, the structure of an energy system can be complex due to its various features and an effective visualization tool requires an integrated design to cover all of these features. With the Canadian energy system, we are dealing with time-varying, spatial and multi-attribute properties simultaneously. We make a general model of the dataset first and choose and design our visualization techniques and interactions accordingly.

Let's first have a look at the structure of an energy system at a specific time and location. The flows between commodities and services within a region can be modelled as a graph $G = (V, E)$ where node $v \in V$ represents different resources, commodities and services such as oil, electricity, heating, etc, and edge $e \in E$ represents a connection. The weight of e, $w(e)$ is the quantity of flow between two nodes. G is a simple, connected, weighted digraph as illustrated in Figure 2. The colors of nodes represent clusters. For example, heat and lighting nodes can be grouped into a more general cluster of residential usage. We will later use clustering to simplify the graph. In this graph, flow is preserved from sources to sinks and the sum of incoming flow is equal to the outgoing flow for every node. "flow networks" [22] are the term to describe this type of graphs. The temporal property of an energy system structure is reflected by changes in the graph topology, i.e. number of nodes and edges between them.

Nodes in a graph can have multiple attributes associated to them. In our energy system dataset, domestic usage, production levels, imports, exports, energy loss and GHG emissions are considered a node's attribute. For example, "electricity" is one of the nodes in the energy system's graph which has specific production, usage, import and export levels. The process of electricity generation produces

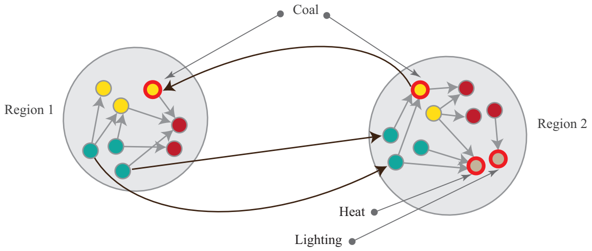


Figure 2: The conceptual model of an energy system. Each region at a specific time has a graph structure. Each sub graph describes the energy system of a specific region. Colored nodes within a graph represent groupings of nodes. Edges linking regional sub graphs correspond to flow between regions.

specific amounts of GHG emissions as well. Production, usage, exports, imports and conversion loss are relevant to the structure of the flow network as the following relationship holds: $imports + production = exports + domestic\ usage + conversion\ loss$. We therefore call these attributes *"dependent"*. On the other hand, we have GHG emissions attributes which are not directly related to the flow network structure and can be considered as *"independent"* attributes.

Among the attributes of a node, import and export also have spatial associations. These attributes not only represent a single value, but also represent a connection to another location. The spatial features of the data set add more complexity to our graph model. Imports and exports extend connections beyond a single region. Having a flow network for every region, imports and exports define incoming and outgoing flow from and to the flow network of other regions. The connections between regional graphs through external flows, generates a larger flow network representing the energy system of a whole country having sub graphs for each province. Figure 2 illustrates the graph model for an energy system. The edges between sub graphs represent flow between regions.

V. VISUAL DESIGN

Based on the tasks and data abstraction, we chose visualization techniques that address each of dataset properties and energy specialists needs. These techniques include:

1) using Sankey diagrams to visualize a flow network.
2) level of detail exploration of Sankey diagrams.
3) smooth animation to visualize temporal changes and level-of-detail.
4) an interactive map for navigating regional flow networks and to visualize imports and exports.
5) changing view in 3D to visualize GHG emissions.

These techniques are described in the following subsections.

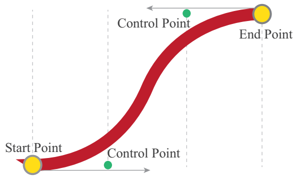


Figure 3: B-spline curve used in Sankey diagrams. Control point positions ensure horizontal tangent vectors at the start and end points.

A. *Flow Network Visualization*

Sankey diagram is a method to show an overview of an energy system and is a familiar tool for energy system specialists. Figure 4 shows a Sankey diagram of Canada in 1978. A Sankey diagram arranges nodes in layers based on the incoming and outgoing edges. In energy systems, resources are usually placed on the leftmost layer and services are on the rightmost layer. In typical Sankey diagrams, edges are represented by a smooth curve where the thickness represents flow quantity.

We employ Sankey diagrams as the main component of our visualization. In our visualization of Sankey diagrams, we represent flows as thick B-Spline curves. The control points are aligned horizontally with the start and end points of the curve to ensure horizontal tangent vectors (Figure 3). We set low opacity for edges to make them distinguishable when they overlap. Node positions in our Sankey diagrams are top aligned. In this allignment nodes in each level are positioned from top to bottom with equal spaces between them. The position of each node in this alignment is:

$$x_i = W/(L-1) * l,$$
$$y_i = \sum_{j=1}^{i-1} h_i + (i-1) * g$$

where x_i and y_i are the x and y positions of i^{th} node in level l, W is the total width of Sankey diagram, L is number of levels and g is the desired gap between nodes. The placement of nodes can be improved using Sugyiama's framework [23] for drawing directed graphs. This framework is composed of several steps for drawing directed graphs such as layering nodes, ordering nodes in each layer and finding exact positions for nodes. The benefit of this framework is that it satisfies a couple of aesthetic criteria such as edge crossing reduction and short edges. We have taken advantage of this framework in Figure 4 to generate a more aesthetically pleasing diagram.

Each node in a flow network is represented by a rectangle. As discussed in IV, several attributes associated with a node in the flow network are dependent to the structure of the flow network. Therefore, we assign separate nodes to these attributes and visualize them along other nodes in the flow network.

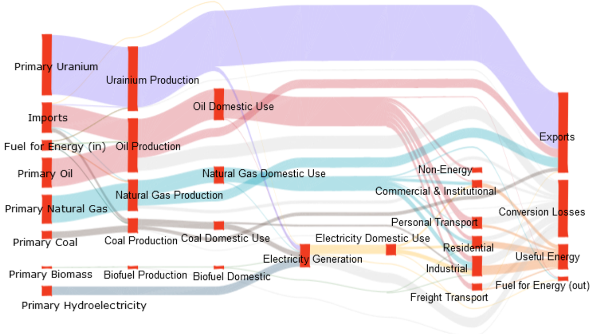
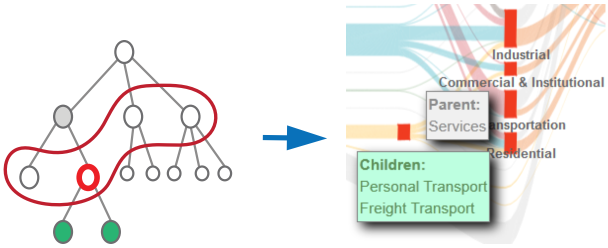


Figure 4: Sankey diagram of Canada in 1978. The layout is calculated using Sugyiama's framework [23]. Several attributes such as imports, exports, usage, production and conversion losses are assigned separate nodes in this diagram.



(a) (b)

Figure 5: Hierarchical exploration of Sankey diagram. (a) a sample hierarchy tree of data. The enclosed nodes are the current nodes visualized in the Sankey diagram. The red node represents "Transportation" node in (b) where the children are "Personal Transport" and "Freight Transport". (b) shows hovering on a node and list of children and parent name appearing.

B. level-of-detail exploration

Despite flow networks in Canadian energy system consisting of a relatively small number of nodes and edges, visualization of Sankey diagrams with all nodes quickly becomes complex as in Figure 1b. As Shneiderman's mantra states: "Overview first, zoom and filter, then details-on-demand" [24], it is also desirable to provide an overview of the energy system and allow users to access details on demand.

We define two main operations on Sankey diagrams to perform level-of-detail exploration: grouping and ungrouping. Grouping aggregates flow and attributes of a set of desired nodes, while ungrouping breaks a node down to its children. These two operations require a hierarchical data structure to be defined for the graphs. We create the hierarchy using data categorization provided by our energy system collaborators. For example, "personal transportation" and "freight transportation" are grouped in "transportation" category as illustrated in Figure 5b. Grouping merges several child nodes into a parent node by summing up their attribute values. It also creates meta edges for the parent node by summing up flow values of its children. Ungrouping is a little less straight-forward. When we move to lower levels of detail, i.e. less detailed information, the higher level connections between nodes is lost. When a parent node is drilled down, the edges from child nodes to their neighbors is recomputed based on the connections of the most detailed graph. The algorithms for grouping and ungrouping operations on weighted graphs are discussed in detail by Auber et al. [25]. To initially view a Sankey diagram, we choose a specific set of nodes in the hierarchy as illustrated in Figure 5a. We create the Sankey diagram by bottom up calls to the grouping operation, starting from leaves in the tree, until we reach desired set of nodes. The hierarchy can be explored interactively by giving the options of grouping or ungrouping upon hovering the nodes as shown in Figure 5b. Figure 1 shows a Sankey diagram in two different levels of detail.

C. Animation for Sankey diagrams

As discussed in II, one of important requirements for energy specialists is to view changes in the Sankey diagrams over time. In this work, we take advantage of animation to represent time-varying data. As the flow values change over time, node dimensions change, causing overlaps between nodes. In order to avoid these overlaps, we use the process illustrated in Figure 6. This process keeps the changes in node positions small compared to recomputing the layout for every single time step. In this process, we start with an initial Sankey layout discussed in Section V-A. Changes in flow and attribute values are reflected in node heights by increasing or decreasing the rectangle sizes from the bottom. When the bounding boxes of two nodes hit, we move the lower node accordingly as illustrated in Figure 6. This relocation may require moving lower nodes as well until no more hits are detected. Once graph layout is defined for each time step, node positions are linearly interpolated to create a smooth animation.

D. Multi-attribute visualization

As discussed in IV several attributes are associated with nodes in the Sankey diagram. We discussed the visualization of dependent attributes in Section V-A. Yet, GHG emissions are the attributes which are associated to some of the nodes in the diagram. Emissions are divided into three separate groups CO_2, N_2O and CH_4, creating three attributes for these nodes. In order to avoid more complexity of Sankey diagrams, we take advantage of 3D view to attach more attributes to each node. In fact, our visualization of Sankey is in a 2D plane embedded in 3D space and emissions are visualized as bar charts perpendicular to this plane. We smoothly change the view from front view to a 3D view (e.g.

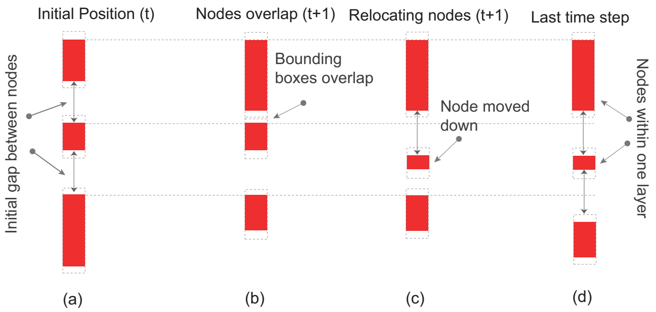


Figure 6: The process of changing Sankey diagram layout during animation. (a) Initial positions of nodes in a level in time step *t*. Gap sizes are set equally between nodes. (b) In *t+1* time step, node dimensions change, causing overlaps between nodes. (c) Second node is moved down by the initial gap size in *t+1*. (d) After animation stops, all nodes are repositioned so they have the initial gap between them again.

the bird's eye view), and attach the emission information to each node as shown in Figure 7. Each bar chart on a node can support visualization of several attributes. We use orthographic projection in order to preserve lengths and to make bar chart comparisons more reliable. The 3D view reveals the structure of attributes all over the nodes while maintaining the structure of the Sankey diagram. Figure 7 shows a Sankey diagram tilted in 3D for revealing different classes of GHG emissions for nodes. It can be seen that comparing individual attributes for each node is easy in this view. To resolve possible occlusions of the bar charts, user can interactively rotate the diagram to achieve a proper view of the bar charts.

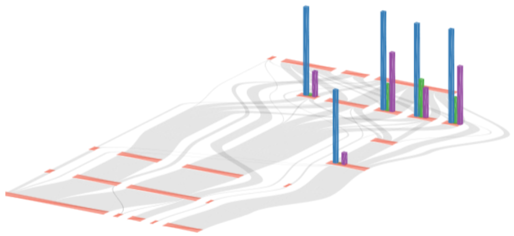


Figure 7: Three categories of emissions shown for each node of the Sankey diagram in 3D. Blue, green and purple represent CO_2, N_2O and CH_4 respectively.

E. Map view

In order to view regional Sankey diagrams, we use an interactive map to easily navigate diagrams for different regions. In this map, regions and the legends are clickable, facilitating interactive exploration of regional Sankey diagrams as well as distribution of energy resources across the map. The benefit of this dual view is that while import and export and total production levels of a specific energy source are revealed using the map, domestic usage patterns can be further tracked down using the associated Sankey diagram to that region.

Interactions: We have designed several interactions between map and Sankey diagrams to make simultaneous exploration of abstract and spatial data possible. Firstly, the interactive map is used to view Sankey diagram of each province separately by clicking on the corresponding province. Secondly, the interactive legend is used to show distribution of specific energy sources or electricity across Canada. Clicking on each of legend elements, reveals a flow map of the corresponding fuel on the map. Figure 9a shows a flow map of refined petroleum trade across Canada in 1978. To refine the import and export results for a specific region, the user can click on a specific province on the interactive map, which reveals the flow map specific to that province (Figure 9b).

The other interaction is to show the imports and exports through Sankey diagrams. User can click a node on the Sankey diagram and if corresponding imports and exports exist, they will be viewed on the map. This interaction also highlights the node and its incoming and outgoing edges. Figure 8 shows the result of interaction with the Sankey diagram and distributions shown on the map.

We also provide an animation slider which runs animation for the map and emissions data as well as Sankey diagrams. It is worth mentioning that except in the Sankey diagrams, we did not face a layout problem in map or emissions and therefore the animation can easily be performed from one time step to the other.

F. Implementation

Our web-based visualization is developed using JavaScript graphics libraries. 2D graphics in the map is implemented using Raphael.js [26]. The Sankey diagram which involves 3D interaction is developed using Three.js library [27] which supports 3D graphics.

VI. DISCUSSION

In this work we provided an integrated visualization tool for the Canadian energy system. However, we find our visualization techniques useful in other fields as well such as financial flow visualization or for other energy systems as far as they have the same structure of data. A limitation of our system is that using 3D for emissions or for multiple attributes of nodes, raises concerns about effectiveness of visualization for comparison. In our dataset, emissions are mainly associated to a specific layer which makes it easier to align the nodes interactively by rotating the diagram. In addition, using orthographic projection can partially eliminate the problem of length distortion. More attributes can also be added to nodes by extending the bar chart representation to glyphs attached to nodes. In this case, interactions to align glyphs should be designed.

(a) (b)

Figure 8: Linked view of spatial data and Sankey diagram. (a) Natural gas node is selected in Sankey diagram. (b) Distribution of natural gas is viewed across Canada.

(a) (b)

Figure 9: (a) Flow map of refined petroleum over Canada. (b) Refined petroleum for a specific province.

VII. FEEDBACK

We consulted with two collaborating experts in energy systems to evaluate our work. According to initial requirements, our energy system collaborators found the new visualization of energy system useful in following terms: They stated having a map in conjunction with Sankey diagrams is a plus for this visualization since you can view the energy system from another window. The traditional visualization of an energy system uses separate visualizations which makes it harder to compare and see different aspects of data. They also mentioned that a map can provide a comparison capability across several regions, as well as spatial information which is not available in a Sankey diagram. Furthermore, viewing emissions is a feature which has not been available in previous visualizations of Sankey diagrams. Emissions are usually provided in separate visualizations and our collaborators stated that changing diagram view in 3D is very useful as it shows all the information in a single visualization. This feature is specially useful for non-experts, i.e. for the public and for the policy makers, as it provides an easier way for exploration of the data.

They also found level-of-detail exploration helpful. They mentioned a simplified version of Sankey diagram is useful specifically when communicating energy systems with people less familiar with this type of visualization. A Sankey diagram, is a complex visualization for people new to it and having the capability to remove the complexity of diagram as well as showing the details, makes Sankey diagrams useful for presentation to a broader audience.

VIII. CONCLUSION

In this paper we presented a visualization tool for supporting exploration of the Canadian energy system. We provided a detailed data abstraction for structure of the energy system and linked visualizations based on data and task analysis. Our employed dataset involves time-varying, spatial and multi-attribute features which require integrated visualization techniques to support exploration of these features simultaneously. We used interactive Sankey diagrams to generate visualization of flows and correlations in an energy system. We also used smooth animation to show variations in Sankey diagrams across time. We designed 3D interaction with Sankey diagram to view GHG emissions as bar charts attached to Sankey diagram nodes. We defined a hierarchical data structure for energy data in order to facilitate level-of-detail exploration in the Sankey diagrams. Linked views between map and the Sankey diagrams were also used for simultaneous exploration of abstract and spatial information. The techniques we provided in this work, are extendable to other energy systems as well as other areas dealing with visualization of flow.

In future work, application of datasets from other domains to our tool, improving animation by finding optimum positions of nodes from one time step to the other and designing a multi-attribute visualization for larger number of node attributes will be considered. We are also interested in incorporating future projections of data provided by energy modelling tools into our tool to make it more useful for analytical purposes.

ACKNOWLEDGMENT

The authors would like to thank Bastiaan Straatman and Benjamin Israel for their help, suggestions and feedback. This work was funded by Canada School of Energy and Environment and GRAND NCE.

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