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ORIGINAL ARTICLE

EnergyViz: an interactive system for visualization of energy systems

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Abstract Energy systems are under pressure to transform to address concerns about climate change. The modeling and visualization of energy systems can play an important role in communicating the costs, benefits and trade-offs of energy systems choices. We introduce EnergyViz, a visualization system that provides an interface for exploring time-varying, multi-attribute and spatial properties of a particular energy system. EnergyViz 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. Finally, we include evaluation results of EnergyViz collected from expert and inexperienced participants.

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1 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 to make energy systems more sustainable requires an understanding of the nature of our existing energy systems.

Sankey diagrams are a type of flow diagram that are commonly used to show the magnitude of energy flows from resources, through commodities to services (see International Energy Agency's website [16] for an example of a Sankey diagram). These diagrams 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 typically require several visualization techniques applied together to show all properties of data.

Energy systems data consist of spatial, time-varying and multi-attribute features as well as flow information that requires advanced visualizations to capture all of this information. In this paper, we introduce a system for visu-

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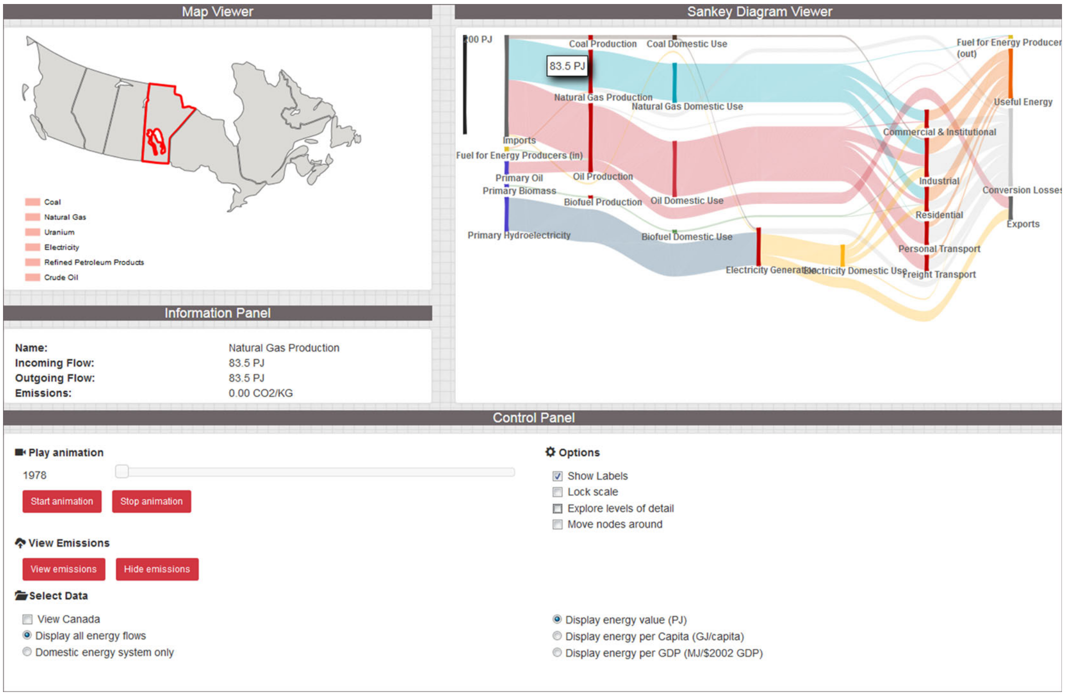

Fig. 1 An overview of EnergyViz

alization of Canada's energy system which handles the complexity of data using linked visualizations (Fig. 1). The main component of EnergyViz is interactive Sankey diagrams. To address the complexity of the energy systems, we support level-of-detail exploration of Sankey diagrams using a hierarchical structure for 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. To illustrate the relationship between these attributes and conventional Sankey, we use smooth animation to change the view. Smooth animation is also used for other aspects of our visualization system including the visualization of temporal changes and increasing or decreasing the level of detail.

EnergyViz, is created using techniques discussed in our previous paper [3]. In [3], we discuss how Sankey diagrams are generated and smoothly animated. In this paper, we improve the layout of a Sankey diagrams and their animation using optimization. We also provide evaluation results of EnergyViz. This evaluation is performed using a qualitative study of both expert and inexperienced participants.

The remainder of this paper is organized as follows. Section 2 presents a background on Energy system and tasks based on which we designed our system. Related work follows in Sect. 4. We discuss data abstraction in Sect. 5. We describe our design choices for different aspects of energy system dataset in Sects. 6, 7, 8 and 9. Evaluation results are presented in Sect. 11, and a discussion of results follows in Sect. 12. This paper ends in Sect. 13 with conclusion and ideas for future work.

2 Energy system background

Energy systems encompass the generation and conversion technologies as well as the distribution network which provides energy services (mobility, light, nutrition, industrial products, etc.) from the energy sources that nature provides. Examples of energy sources include 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 paper, we use data from the Canadian Energy Systems Simulation (CanESS) model [9]. CanESS draws on historical data from a range of government sources and creates an integrated model of energy flows and GHG emissions by Canadian province for the period 1978–2010. This historical model is then used to project the future of Canadian energy system 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 throughout the process of energy generation to delivery. We use such historical data for Canada provided by CanESS in our visualization.

3 Motivation and tasks

Our project was motivated by the need of our energy system expert collaborators for sophisticated visualizations that can be used both by the public and by policy makers to understand the features of Canada's energy system.

While Sankey diagrams have been widely used in visualizing energy systems, they can be criticized in different ways. A Sankey diagram is often too complex particularly when populated with highly detailed information, making it difficult to see important aspects of the energy system being represented. Besides, other important information such as GHG emissions cannot be simply added to a Sankey diagram as it increases its visual complexity.

In summary, based on discussions we had with our collaborators, we aim at achieving the following goals using EnergyViz:

1. Being able to show temporal changes in Canada's energy system. This feature is particularly important when wanting to compare historical differences among regions, or alternative energy futures. Such insights are particularly valuable for decision makers as they consider different policies and investment strategies;
2. Reducing visual complexity of Sankey diagrams by viewing them at different levels of detail;
3. Visualizing GHG emissions as an important feature of energy systems that is driving the change in these systems.

4 Related work

The design of EnergyViz draws upon research in several related domains including: visualization of flow, time-varying data visualization and linked visualizations.

Visualization of flow Visualization of flow, i.e., showing the amount of change from one state or element to another, appears in many application areas. A previous system which directly addresses visualization of energy systems is the work by Riehmann et al. [21]. In this work, visualization of energy system of a city using interactive Sankey diagrams is addressed. The other example of using flow diagrams is Outflow system [28]. In this system, temporal event sequences are visualized using edges between time steps to show progression of an event. Another example system which uses parallel sets [5] technique to show people's movement information from one group to another is the work done by von Landesberger et al. [27]. In their approach, parallel sets are used to show change in classes of data over time.

Furthermore, several works focus visualization of flow on a map. Phan et al. [11] initially introduced techniques for visualizing flows on a map (flow map) and presented algorithms for optimizing layout of flow maps and reducing visual clutter. In EnergyViz, we use a basic flow map representation to show energy imports and exports on a map.

Time-varying data visualization There is a vast literature on visualization of time-varying data [2,18]. Various techniques to visualize time focus on either static representation of all time steps in 2D or 3D space or dynamic visualization using animation [1]. Small multiples [26] 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. [17] suggest a clustering technique to reduce the number of maps required to represent data.

Animation is also used as a common technique to show temporal changes. Arguments exist around effectiveness of animation to visualize trends [22,23]; however, animation has proved successful for presentation and viewing results of analysis [1,23]. Gapminder [13] is an example of a successful use of animation in information visualization.

Several previous work discuss creating smooth animation for dynamic graphs to maintain the so-called *mental map*. GraphAEL [12] is an application for animating graphs with evolving layouts. In this application, force-directed layout is modified using between-timestep edges to preserve the stability of animation. Also, North et al. [19] discuss preserving mental map during animation of static directed graph drawings by taking into account the geometrical and topological information of the graph.

Linked visualization Our system presents a combination of visualization techniques to facilitate exploration of different features of an energy system. Several systems have been previously proposed to support spatio-temporal and multivariate features of a dataset. An example system is VISSTAMP [14] which provides a framework for visualization of spatio-temporal multi-attribute datasets. VISSTAMP models such datasets as a cube having three dimensions of location, multiple attributes and time. This framework suggests a separate visualization technique for each dimension and links them together to facilitate data exploration. Graphdice [6] is another example system which uses linked visualization for multi-attribute social networks. Also, VisLink [10] is a visualization tool which addresses linking several visualizations through edges that connect same entities across several visualizations.

5 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.

Energy systems can be modeled as a *network flow* [7] which is a weighted directed graph with specific properties. In a network flow, there are three types of nodes including source nodes, intermediate nodes and sink nodes. The source nodes produce flows and sink nodes are where the flows end. Intermediate nodes are the nodes other than sink and source nodes which consume a flow. In an energy system, the flow is preserved from sources to sinks and for each intermediate node (Fig. 2a).

The temporal property of an energy system is reflected as the change in its graph topology. Therefore, an energy system is indeed a dynamic network flow.

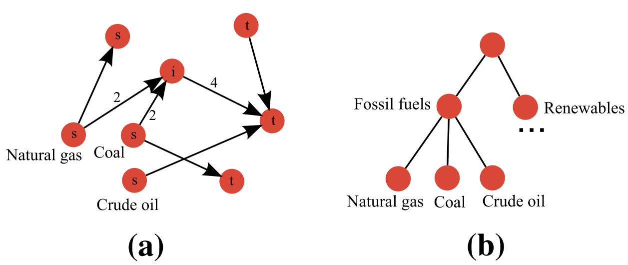

Fig. 2 **a** A sample network flow for an energy system. Source, intermediate and sink nodes are marked with *s*, *i* and *t*, respectively. *Numbers* represent edge weights. **b** A sample hierarchy for an energy system network flow

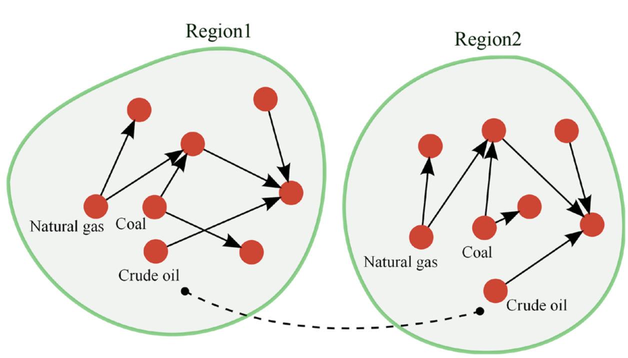

Fig. 3 Illustrating energy system graphs of two regions. The *dotted line* between crude oil nodes shows how two regional network flows might have spatial connections through imports and exports of a source or commodity

In the energy system graph, nodes can have multiple attributes associated with them. Domestic usage, production levels, imports, exports, energy loss and GHG emissions are examples of a node's attributes.

Among the attributes of a node, import and export have spatial associations. These attributes not only represent a single value, but also represent a connection to another location. The spatial features of the dataset add more complexity to energy system graph model. Figure 3 shows an overall model of an energy system. This figure shows two regional network flows connected to each other through spatial attributes such as imports and exports.

Furthermore, to make level-of-detail exploration of a Sankey diagram possible, we associate the energy system graph with a hierarchical data structure. This hierarchy makes energy system graph a clustered graph. A clustered graph consists of a graph and a tree which defines the existing hierarchy of the nodes of the graph [8] (Fig. 2b).

In the following sections, we discuss the visualization technique choices for each of the dataset features.

6 Network flow visualization

In order to visualize regional network flows discussed in Sect. 5, we use Sankey diagrams, a familiar tool for energy system specialists.

In a Sankey diagram, nodes are arranged in layers where 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 (Fig. 4).

Assigning layers to nodes in a Sankey diagram is done so that all the edges point to the same direction and no edges exist between nodes of the same layer. Healy and Nikolov [15] discuss layer assignment algorithms for *layered graph drawing*.

Having the layer for each node, finding the x positions of nodes is trivial by evenly distributing layers in the drawing area [3].

In order to achieve readable Sankey diagrams, we consider several aesthetic criteria. These criteria include minimum edge crossings, short-as-possible edge lengths and straight edges. These criteria as well as steps of calculating Sankey diagram's layout are adapted from Sugyiama's layered graph drawing framework [24].

6.1 Reducing edge crossing

Edge crossing is an important factor which affects readability of a graph. In layered graph drawing, the order of nodes in a layer determines number of edge crossings. One of the heuristics for finding node ordering is barycen-

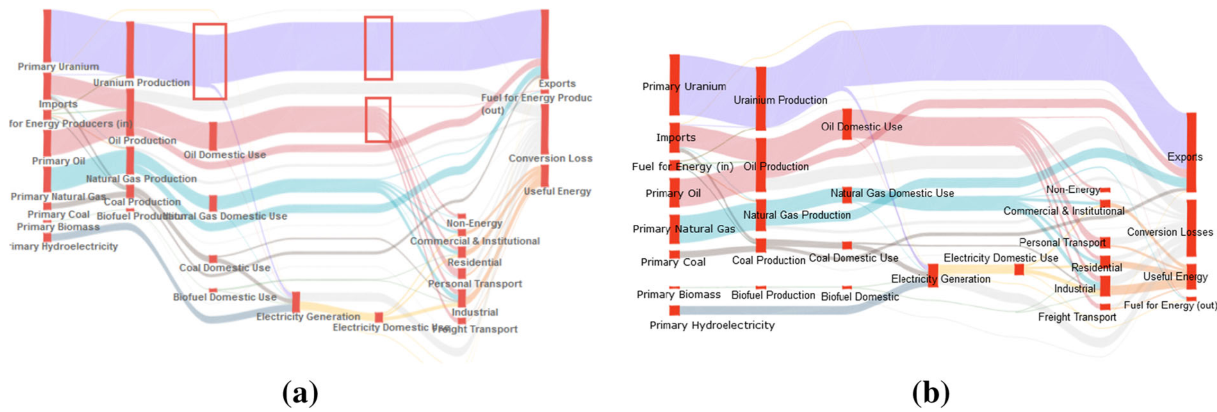

Fig. 4 **a** A Sankey diagram generated using simple layout. *Red rectangles* mark several dummy nodes—nodes that are added to avoid edge and node intersections. **b** Sankey diagram of Canada in 1978. The layout is calculated using optimization

tric method [24]. This method orders nodes in a layer by computing each node's barycentric position considering its predecessor (direct parent nodes) or successors (direct child nodes).

6.2 Assigning y coordinate to nodes

Once horizontal positions of nodes and their orders are determined, we use two different algorithms to find the vertical position of each node in a layer.

Simple layout In this layout, node positions are top-aligned, i.e., nodes in each layer are positioned from top to bottom with equal spaces between them [3]. Figure 4a shows an example of a Sankey diagram generated using simple layout. Notice that, in order to avoid edges passing over nodes, we add *dummy nodes* to the graph to replace long edges with edges that connect nodes of consecutive layers (Fig. 4a). Adding dummy nodes is also important for reducing computational complexity of finding layout using optimization.

Optimized layout In order to improve the placement of nodes and to achieve our aesthetic criteria, we use an optimization model. Here, we wish to minimize the weighted sum of distances between each two connected nodes in consecutive layers. By considering edge weights, we enforce edges with larger flows to be shorter. In addition, several inequality constraints (e.g., node ordering obtained from Sect. 6.1 apply to this minimization problem. Therefore, we model this optimization problem to linear programming. The objective function is defined as:

$$f_1 = min \sum_{i=1}^{N} w_i * |y_j - y_i| \tag{1}$$

where y_j and y_i are y positions of two connected nodes in layers j and i, respectively, N is the number of edges and w_i is the weight of the edge connecting nodes. Note that due to adding dummy nodes to the graph, the existing edges are always between nodes of two consecutive layers.

Several constraints apply to this optimization problem. First, we should respect the node ordering in each layer obtained from reducing edge crossing (Sect. 6.1). This constraint is expressed as $y_{i+1,j} > y_{i,j}$ where $y_{i,j}$ is the y position of ith node in layer j. Second, the diagram should be drawn within boundaries of the drawing area. Therefore, $y_{first} < top$ and $y_{last} > bottom$ must apply for the first and last nodes in each layer. Finally, we wish to keep flows as straight as possible by keeping connected dummy nodes aligned. This constraint is expressed as $d_i = d_j$ where d_i and d_j are two connected dummy nodes. This constraint reduces the unnecessary curves throughout a single flow.

This linear programming can be solved using simplex algorithm implemented in Numeric.js library [20]. See Fig. 4b for a Sankey diagram resulting from optimized layout.

6.3 Visualizing flows

In our visualization of Sankey diagrams, we represent flows as thick cubic Bezier curves. In order to ensure tangent continuity of connected flows at dummy nodes which makes a single flow appear smooth and continuous, we position control points as in Fig. 5a. In this figure, P_0 is aligned horizontally with P_1 and P_2 is aligned horizontally with P_3. In order to enlarge the thickness of this Bezier curve, we use the method proposed by Tiller and Hanson [25]. In this method, control point polygon is offset in perpendicular direction to find the positions of new control points (Fig. 5b).

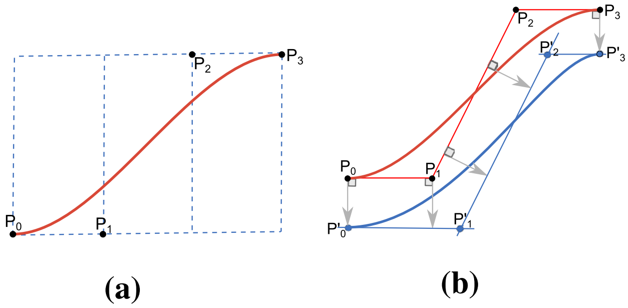

Fig. 5 Creating flows in the Sankey diagrams. **a** Cubic Bezier curve used in our Sankey diagrams. Control point positions ensure *horizontal tangent vectors* at P_0 and P_3. **b** Using Tiller Hanson algorithm for creating offset curve of a cubic Bezier curve. *Red* is the original curve, and *blue* is the offset curve

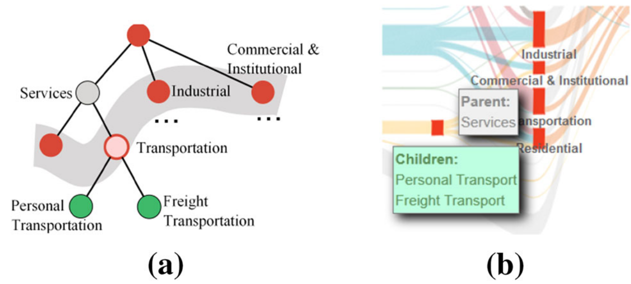

Fig. 7 Hierarchical exploration of Sankey diagram. **a** A sample hierarchy tree of data. The enclosed nodes are the current nodes visualized in the Sankey diagram. **b** The hovering interaction for hierarchy in **a**. Hovering over *Transportation* node shows Services as parent and *Personal Transportation* and *Freight Transportation* as children

7 Level-of-detail exploration

Despite network flows 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 shown in Fig. 6a. Therefore, it is desirable to provide an overview of the energy system and view 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 (Fig. 7a).

We create the hierarchy using data categorization provided by our energy system collaborators. For example, "personal transportation" and "freight transportation" are grouped into "transportation" category. 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, however, is a little less straightforward. When we merge several nodes in a graph, the connections between child nodes are lost. Therefore, when a parent node is drilled down, the edges from child nodes to their neighbors are 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. [4].

To initially view a Sankey diagram, we choose a specific set of nodes in the hierarchy as illustrated in Fig. 7a. 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 Fig. 7b. Figure 6 shows a Sankey diagram in two different levels of detail.

8 Animation for Sankey diagrams

As discussed in Sect. 2, one of the important requirements for energy system experts is to view changes in the Sankey diagrams over time. In this work, we take advantage of animation to represent time-varying data.

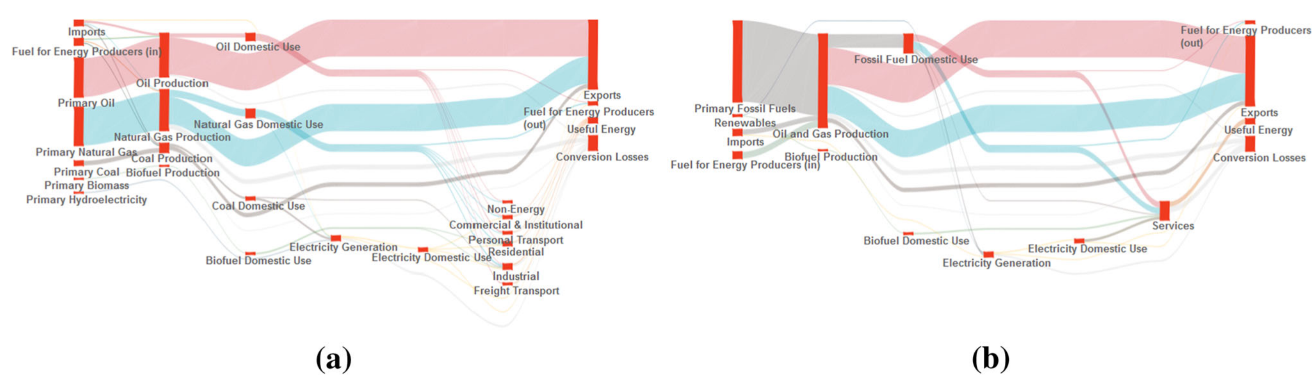

Fig. 6 Visualization of Canadian energy system using level-of-detail exploration. **a** A Sankey diagram with many details. **b** A simplified Sankey diagram

As the flow values change over time, node dimensions change in the Sankey diagram, causing overlaps between nodes. Assuming changes in flow and attribute values are reflected in node heights by increasing or decreasing the rectangle sizes from the bottom, one way to avoid these overlaps is to move nodes down each layer as they overlap. This method is discussed in [3].

However, animation can be improved by minimizing the overall movement of nodes in the diagram between two time steps. Fewer movements during animation make it easier for the observer to follow the changes.

To minimize node movements from one frame to the next, we minimize sum of vertical movements of the nodes between frames:

$$f_2 = \sum_{i=1}^{N} |y_{i,t} - y_{i,t-1}| \quad (2)$$

where $y_{i,t}$ is the y position of ith node in time step t.

The overall objective function for the optimized animation is a trade-off between having the aesthetic criteria of the optimized layout (Sect. 6) and minimizing the node movements. Considering Eqs. 1 and 2, the overall objective function for animation is:

$$f = cf_1 + (1-c)f_2, \quad 0 \le c \le 1$$

One drawback of creating animation using optimization compared to simple method discussed in [3] is that, here we precompute the layout in each time step. The precomputation of node positions is necessary in this method due to time complexity of simplex algorithm.

9 Multi-attribute visualization

As discussed in Sect. 5, there are several attributes associated with a node in the network flow. Some of these attributes such as production level can be visualized as a separate node in Sankey diagram. This choice is particularly useful as production level is directly related to amount of energy flow in an energy system. Having such an attribute visualized as a node in Sankey diagram can show the relationship between the attribute value and flow.

However, other attributes such as GHG emissions are totally independent of flow values. Furthermore, integrating too many attributes as nodes in Sankey diagram makes it even more complex. We therefore examine visualizing three categories of emissions (CO_2, N_2O and CH_4) by augmenting Sankey diagram view in 3D (Fig. 8).

In this technique, 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., the bird's eye view) and attach the emission information to each node. 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 for all nodes while maintaining the structure of the Sankey diagram. To resolve possible occlusions of the bar charts, the diagram can interactively be rotated to achieve a proper view of the bar charts.

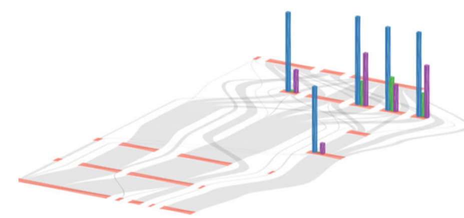

Fig. 8 Three categories of emissions shown for each node of the Sankey diagram in 3D. *Blue*, *green* and *purple* represent CO_2, N_2O and CH_4, respectively

10 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 legend 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. The map and Sankey diagram are connected using linked views (Fig. 9), making association of spatial and abstract information clear. For more details, refer to [3].

11 Feedback and results

In order to validate the usability of EnergyViz, we perform a formal evaluation of different functionalities of EnergyViz discussed in this paper. In this section, we describe evaluation participants, procedure and results.

11.1 Participants

EnergyViz is targeted toward energy system experts as well as a less experienced audience interested in exploring energy systems. We therefore perform our evaluation on two groups of participants.

The first group was made up of two experts with solid background in energy systems who are also familiar with Sankey diagrams.

(a) (b)

Fig. 9 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

The second group are eight graduate students with some background in energy systems and having little or no familiarity with Sankey diagrams.

Furthermore, we collaborated with three energy system experts through out development of our application. We present and discuss comments from the participants as well as our collaborators in Sect. 11.3.

11.2 Procedure

We provided our participants with a questionnaire including questions about each of the features of the EnergyViz including general functionality of EnergyViz (map, animation and Sankey diagram layout), level-of-detail exploration and 3D view of Sankey diagram. We provided the same set of questions for both groups of participants.

For each of the features, we started by giving a demo of the feature as an instruction for how to use it in EnergyViz. Then, we asked participants to work with the feature to aid them in performing a specific task.

For example, to examine the general usability of EnergyViz, we asked participants to read flow values between same elements in two different provinces and then compare them. Then, we asked them to report the trade information of a particular resource.

For the level-of-detail exploration and 3D view, the participants worked with these features and reported how understandable and useful they find the feature.

11.3 Results

In this section, we first provide feedback from our collaborators and then provide feedback of evaluation participants.

The feedback provided by our collaborators was gathered throughout development of our application. Our energy system collaborators found the new visualization of energy system useful in following terms:

1. They stated having a map in conjunction with Sankey diagrams is a benefit for this visualization since you can view the energy system from another window. Maps can also provide a comparison capability across several regions, as well as spatial information which is not available in a Sankey diagram.
2. Viewing emissions is a feature that has not been available in previous visualizations of Sankey diagrams, and changing to the 3D diagram view is very useful as it shows all the information in a single visualization.
3. 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.

Following we provide feedback gathered during evaluation sessions.

General comments Our expert participants provided positive feedback regarding the overall functionality of our application.

One of the expert participants commented that our visualization is certainly useful for the expert user because very few people have an understanding of the overall energy system. Sankey is providing an overview, while experts usually have an insight into their own area of expertise. Our visualization tool can expand their understanding of other aspects of an energy system. Also, one expert and one non-expert participant found our application particularly useful for teaching energy system to inexperienced people.

These participants also found having a map alongside the Sankey diagram a good feature. One participant described the map alone as being *as informative as the Sankey diagram*.

While both expert and inexperienced participants did not have problems with our Sankey diagram layout, they found Sankey diagrams complex by nature. Furthermore, all participants found our animation of Sankey diagram good for seeing the changes in energy system.

Level-of-detail exploration Our expert participants were excited with level-of-detail functionality in the Sankey diagram. One of them believed that the idea is great particularly if very detailed information is available to explore the hierarchy more deeply. She found this feature useful for educational purpose. As she mentioned, they call Sankey diagrams "Spaghetti diagram" and her students find working with Sankey diagrams very difficult at the beginning.

Emissions Most of our participants (eight out of ten) liked 3D emissions visualization. The other two participants did not find 3D view useful. An expert participant was excited with the way we were visualizing the emissions and mentioned that it is "very simple to work with." Another participant preferred 3D to 2D and mentioned "3D looks less cluttered and cleaner compared to 2D".

On the other hand, one of our expert participants did not find 3D emissions very useful because she believed viewing trends is more important about emissions which is not available in 3D view.

Most participants found 3D mostly useful for having an overall view and not for detailed analysis. They preferred the option to have both 3D and 2D emissions to get both overview and detail analysis.

12 Discussion of results

Level-of-detail exploration is an interesting and useful feature for both expert and inexperience users. We find Sankey diagrams very complex for most people, and simplifying them is a useful feature to make understanding them easier. However, one of the problems with current level-of-detail interaction is that viewers are not provided with explicit hierarchy and are left to figure this out for themselves.

One of the major suggested features particularly by our expert participants is viewing future projections of an energy system. As an expert participant mentioned, policy makers and expert users are more interested in testing different policy measures and seeing how they affect the future of an energy system than seeing the historical data only.

13 Conclusion and future work

In this paper, we presented EnergyViz, a visualization system for supporting exploration of the Canadian energy system. We provided a detailed data abstraction for structure of the energy system and discussed our visualization choices. Our employed dataset involves time-varying, spatial and multi-attribute features which requires 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 described using optimization for creating Sankey diagram layout and smooth animation which are an improvement over our past techniques of visualizing and animating Sankey diagrams.

We also described 3D interaction with Sankey diagram to view GHG emissions as bar charts attached to Sankey diagram nodes. Besides, 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. Finally, we evaluated EnergyViz by performing a qualitative study.

The techniques we provided in this paper could be extendable to other energy systems as well as other areas dealing with visualization of flow. One future work is to explore application of our techniques to data from other domains. EnergyViz techniques could be applied to financial flow and ecosystem visualization.

During our evaluation sessions, we received several comments about incorporating more data into our tool. For example, one participant suggested once oil flow is visualized on the Sankey and trades are shown on the map, it would be beneficial for the analysts to include oil well information. Also, an expert participant suggested when running animation for historical data, it is good to know why some significant changes happen in the energy system; for example, if it is due to a crisis. Considering integration of more data, we prospect using techniques of this work in a broader framework such as digital earth. The future work in this regard could be visualizing Sankey on the globe and also sourcing more data related to energy systems and using linked visualizations to show the information.

Incorporating future projections of data is another important direction. Viewing the future implications of data is one of the major tasks that people working in energy systems require. Several parameters such as applying different policies, economic factors, energy prices and moving toward different energy resources would impact the structure of an energy system in the future. The ability to run scenarios based on different parameters and see the future projections would definitely be advantageous for analysis purposes.

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