Using Sankey Diagrams to Map Energy Flow from Primary Fuel to End Use

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Abstract

The energy sector is the largest contributor to gross domestic product (GDP), income, employment, and government revenue in both developing and developed nations. But the energy sector has a significant environmental footprint due to greenhouse gas (GHG) emissions. Efficient production, conversion, and use of energy resources are key factors for reducing the environmental footprint. Hence it is necessary to understand energy flows from both the supply and the demand sides. Most energy analyses focus on improving energy efficiency broadly without considering the aggregate energy flow. We developed Sankey diagrams that map energy flow for both the demand and supply sides for the province of Alberta, Canada. The diagrams will help policy/decision makers, researchers, and others to understand energy flow from reserves through to final energy end uses for primary and secondary fuels in the five main energy demand

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sectors in Alberta: residential, commercial, industrial, agricultural, and transportation. The Sankey diagrams created for this study show total energy consumption, useful energy, and energy intensities of various end-use devices. The Long-range Alternative Energy Planning (LEAP) model is used in this study. The model showed that Alberta's total input energy in the five demand sectors was 189 PJ, 186 PJ, 828.5PJ, 398 PJ, and 50.83 PJ, respectively. On the supply side, the total energy input and output were found to be 644.84 PJ and 239 PJ, respectively. These results, along with the associated energy flows were depicted pictorially using Sankey diagrams. The Sankey diagrams reveal the current efficiencies within various end-use sectors and could help identify options for improving energy efficiency in order to reduce GHG emissions.

Keywords: Energy flows; LEAP model; Sankey diagrams; energy sectors; Alberta; Canada.

1. Introduction

Energy is the backbone of the global economy and supports the lifestyle the world enjoys. However, energy consumption has had consequences that have resulted in a global energy and environmental crisis. Global energy demand is increasing with a high rate due to industrialization and population growth [1]. The global energy demand depends on mainly liquid and solid fossil fuels [2]. Improving energy efficiency is one of the most effective means of reducing GHG emissions and stabilizing CO_2 emissions. Ma et al. argued that energy efficiency improvement programs could contribute to 50% of the global CO_2 savings by 2030 [3]. The design and implementation of efficiency improvement programs require a thorough understanding of both energy demand and energy supply. It is, therefore, important to study the various energy flows involved in a system.

In Canada in 2009, the expenditure on energy for heating and cooling alone was about $152 billion (equivalent to 11 % of GDP). The province of Alberta has one of the largest hydrocarbon bases in North America and is one of the leading Canadian provinces for energy production. Alberta's energy sector is directly and indirectly the largest contributor to provincial GDP, income, employment, and government revenue [4]. The total energy consumed in the five energy demand sectors (residential, commercial/institutional, industrial, transportation, and agricultural) was 968 PJ in 2010. The industry sector accounted for the largest share (50%), followed by transport (24%), residential (12%), commercial/institutional (11%), and agriculture (3%). The energy used by these five sectors produced 107 Mt of GHGs in 2010 [5]. For the province of Alberta, efficient production, conversion, and use of energy sources could help reduce total energy consumption and the environmental consequences. Hence it would be helpful to understand in detail the energy flows in the energy demand and supply sectors. In this paper an attempt is made through Sankey diagrams to identify opportunities to improve energy efficiency in Alberta.

Sankey diagrams are tools for visualizing processes. In this study, the diagrams were used to map energy consumption and transformation from source to end use, efficiencies of various end-use devices, and global energy flow. Arrows and lines are used, with the width of the arrow representing energy intensity.

Several different process visualization tools are described in the literature. Graveland discussed process visualization tools and their application in studying exergy, energy, mass, volumetric flow in energy, and chemical processes, and highlighted the importance of a process visualization tool called EXAN PRO [6]. Neugebaeur et al. described virtual reality tools for process visualization and specifically the conversion of 2-D Sankey diagrams into 3-D diagrams [7]. The study discussed advantages of using process visualization tools to better understand the efficiencies of various processes in the energy flow analysis during product development in mechanical engineering. Szargut J et al., 1988 discussed exergy losses of thermal, chemical, and metallurgical processes through band diagram [8]. The authors proposed a FEA (finite element algorithm) for interactive and efficient handling of energy efficiency problems.

For energy processes, visualization tools are particularly used to study global energy flow, efficiencies at various stages, and transformations with the aim of identifying measures to reduce GHG emissions. Ma et al. evaluated and validated various data sources and represented energy transformation in China in a Sankey diagram [3]. Those authors observed that Sankey diagrams help in the analysis of global energy flow by allowing users to identify options for energy efficiency improvement in passive systems and to project future scenarios. Cullen and Allwood established the importance of energy efficiency improvement for a successful reduction in GHG emissions [9]. Those authors described the historical evolution of Sankey diagrams and developed Sankey diagrams to map global energy flow from fuels through to the final energy end use. They used the findings from the energy flow analysis to project future scenarios.

Lombard et al. used Sankey diagrams to illustrate energy flow in heating, ventilation, and air conditioning (HVAC) systems [10]. These systems were chosen because they account for more than 50% of the total energy consumption in buildings. The diagrams illustrate energy carriers and their transformation in the delivery of thermal comfort services (heating or cooling). Cullen and Allwood suggested that efficiency measures should be focused on those sections in the energy flow that result in maximum energy savings, and for their study they calculated total absolute potential to reduce energy demand and GHG emissions in the energy chain [11]. They also analyzed loss mechanisms and conversion losses that result from these mechanisms. The results were represented in Sankey diagrams.

In the present study, energy flow and energy intensities for various end uses in the five energy demand sectors and different supply sectors (both conventional and non-conventional) are illustrated on Sankey diagrams. Little has been published on the useful and rejected energy in the different energy sectors of Alberta. The purpose of this paper is to address the useful energy and rejected energy considering primary energy inputs for different sectors of Alberta. This is done by using Sankey diagrams that illustrate energy use in the five energy demand sectors and various supply sectors such as coal, natural gas, wind, hydro, biomass, and others. The LEAP model is used to find the input and output energy based on end-use technologies energy intensities.

2. Methodology

2.1 *Long Range Energy Alternatives Planning System (LEAP) model*

For this study, Sankey diagrams were drawn using output from an energy-environment planning and forecasting tool called the *LEAP*. The LEAP model has been used for energy systems planning [12-14], sector level analysis [15-18], GHG mitigation analysis [19-22] and other purposes. The LEAP modeling methodology is based on building the energy use and supply database and extending it further to simulate various scenarios of energy demand and supply.

The Alberta-specific *LEAP* models the characteristics of the energy supply and demand sectors. *LEAP* can be used as an energy accounting tool to study the physical description of an energy system or to estimate the GHG abatement potential, the costs associated with the energy systems, and other environmental impacts.

The *LEAP* model for Alberta is made up of four modules: demand, transformation, electricity generation, and resource. The demand module details the end-use energy demand for primary and secondary fuels in the five main energy demand sectors in

Alberta. These energy demand sectors are further divided into subsectors. For example, the residential sector is divided into rural and urban subsectors. These subsectors are further divided according to end-use energy such as that used for cooking, lighting, heating, etc. Each end use is associated with different types of energy-consuming devices. In our study, data specific to each of Alberta's energy demand sectors, subsectors, end uses, and devices were derived using the *LEAP* model. The transformation module consists of all the energy conversion processes: electricity generation, oil refining, coal mining, etc. The electricity generation module includes characteristics of all power plants currently operating in Alberta plus those planned for the future. The electricity-generation planning of various agencies has been analyzed, and, based on the analysis; data were derived using the *LEAP* model. The resource module deals with the energy sources available in Alberta. The *LEAP* model has its own built-in database called the Technology and Environmental Database (TED) that contains emissions factors for different fuels and transformation technologies [23]. From the output of these *LEAP* modules (using Alberta-specific data), we made Sankey diagrams for the province's demand and supply sectors.

The assumptions and input parameters for the *LEAP* model are presented in the following sections. Next, the methodology for making the Sankey diagrams is discussed. Finally, the key findings and the results are presented.

2.2. Key assumptions and inputs for the use of the *LEAP* model

Data for our use of the *LEAP* model were found in various reports and databases. The data were used to develop the energy demand and supply modules for Alberta for the base year 2005. Once the base year data were entered into the *LEAP* model, a business-as-usual scenario was developed using various factors over a planning horizon of 25 years, i.e., from 2005-2030. In this study, the business-as-usual scenario is called the reference scenario. The reference scenario gives a quantitative description of the energy demand and supply situation for the 25-year study period. As a method of validation of the model, the estimates based on the model's results for the year 2009 are shown in the results section.

In the *LEAP* model, various results were generated based on reports and data from Natural Resources Canada [24], the Energy Resources Conservation Board [25], the Alberta Electric System Operator [26], Statistics Canada Energy Division [27] , the National Energy Board [28], and the Canadian Energy Research Institute [29].

The supply and demand scenarios are driven by end use and categorized according to end-use energy consumption, energy conversion, and energy available. The data for all the sectors and subsectors were organized hierarchically and in the form of a tree. The energy demand and supply trees are discussed in subsequent sections. Each of the sectors is modeled for its specific energy consumption and end-use fuels along with environmental loads under demand, transformation, electricity generation, and resources modules.

The demand module comprises the five energy demand sectors: residential, commercial, industrial, agricultural, and transportation. The energy is consumed by end users (or end-use devices) to carry out specific activities under these sectors. The energy consumed in different end uses during a particular time period is entered in the *LEAP* model as separate end-user branches within each sector.

Each sector was modeled based on the type and number of end-use consumers. Each of these sectors is further segregated into a final end-user level. The end use is segregated by different types of primary and secondary fuels, e.g., natural gas, electricity, petroleum, etc. Hence a highly elaborate and comprehensive database is generated for each sector. End-user energy demand is expressed as a per-unit of end-use activity depending on the sector, e.g., for the household subsector, energy demand is expressed as MJ/household; for the commercial sector, energy demand is expressed as MJ/m^2.

The three key parameters entered are activity level, final energy intensity, and environmental data pertaining to the different branches. Each of the branches of Alberta's energy demand sector has a different parameter as the basis of simulation. Table 1 summarizes the basic assumptions of modeling for each energy demand sector [30-32].

2.1 Methodology for developing a Sankey diagram

Sankey diagrams are specific types of flow diagrams in which the width of the arrow is in proportion to the quantity of flow. These diagrams are typically used to illustrate energy or material transfers between processes. The diagrams help in understanding a particular system's energy flow in each demand and supply sector of Alberta [33]. For this study, we analyzed energy flow in each of the energy demand and supply sectors' subsectors, final energy end use, and energy intensity specific to end-use devices.

Energy intensities of specific end-use devices were assessed based on the aggregate energy intensities found in the literature and energy efficiencies of the end-use devices. Energy efficiency was assessed in two ways in this study. First, the efficiency of specific end uses such as lighting, space heating, etc., was assessed, followed by an assessment of the final energy intensity/efficiency of the end-use devices. The results of the two were combined to give an overall efficiency and to estimate both the useful and the rejected energy. This was done for the entire demand tree under different energy demand sectors. The amounts of useful and rejected energy for electricity generation in the supply sector were similarly estimated. Rejected energy refers to "loss of energy" due to system loss, transmission and distribution loss, loss of energy because of end use technology efficiency and also losses according to second law of thermodynamics. The estimates for the other energy supply sectors (e.g., demand for auxiliary fuels in supply sector) were grouped under the industrial sector. Software called "e!Sankey pro" was used to develop the Sankey diagrams showing Alberta's energy flow [34]. The data are based on the output from the *LEAP* model.

3. Results and Discussion

3.1 Residential sector Sankey diagram

Alberta’s residential sector can be classified into the following subsectors: single detached, single attached, apartments, and mobile homes [33]. Based on the LEAP model, the estimated energy consumption shares are 76%, 8%, 11% and 5% in single detached, single attached, apartment and mobile home, respectively.

Energy end-use demand in the residential sector is classified into four major end uses:

- Lighting
- Appliances
- Space heating
- Water heating

Total energy consumption was 7 PJ in 2009. Due to less efficiency of bulbs, the useful energy was 2 PJ and the remaining 5 PJ was rejected energy for lighting. The estimated end-use efficiency of lighting in 2009, then, was about 29%.

The highest demand for energy in the residential sector is in space heating. In 2009, 119 PJ were used for space heating. Based on the *LEAP* model output, it was found that fuels mostly used for space heating are natural gas (119 PJ) and petroleum products (1 PJ); a small amount of electricity (5 PJ) and biomass (0.4 PJ) are also used. Total energy used was about 126 PJ for space heating. For space cooling total energy used was about 37 PJ (natural gas 36, electricity 1, oil 0.1 and biomass 0.05 PJ). Space heating furnaces in Canada have an average fuel efficiency of 80-95% [35]. Based on heat losses from doors and windows and a lack of proper insulation, the actual energy efficiency of space heating was considered to be about 60% [36]. The total heat lost from standard homes is estimated to be somewhere between 13 and 23%, mainly due to a lack of air sealing and insulation [37]. The total useful energy in space heating, therefore, is estimated to be about 76 PJ and the total rejected energy is about 50 PJ.

Residential appliance energy end users are refrigerators, freezers, dishwashers, dryers, and electronic equipment. Improvements in the energy efficiency of new appliances resulted following the introduction of minimum efficiency standards in the 1990s [5]. Estimated major household appliances energy consumption are; refrigerator 410, freezer 420, dishwasher 80, cloth washer 40, cloth dryer 980 and range 700 kWh/year/household [5]. The useful energy of the appliances is calculated on the basis of a motor efficiency of 90% [36]. The useful energy is estimated to be 17 PJ out of 19 PJ of input energy; the rest is rejected energy.

[Figure 1]

The energy demand for water heating in 2009 was 37 PJ. Of this, 30 PJ were useful energy and 7 PJ were rejected energy. The estimate is based on the assumption that boilers are 80-85% energy-efficient [5].

Figure 1 is a Sankey diagram that shows the energy demand for Alberta's residential sector in 2009 with detailed end uses. The primary energy sources are coal, petroleum products, and natural gas, along with some renewables such as hydro and wind. The fuel used most in the residential sector is natural gas; about 162 PJ was used in 2009. Oil demand in the residential sector is low – it was only 1 PJ in 2009. The main secondary energy is electricity. The total electricity input to Alberta's residential sector was 26 PJ.

The Sankey diagram also shows the total energy end use as well as the useful and rejected energy. Out of a total input energy of 189 PJ to Alberta's residential sector in 2009, the amount of useful energy was 125 PJ and the rejected energy was 64 PJ.

The remaining energy input and output flows and the corresponding useful and rejected energy are shown in Figure 1 as "Other Demand Sector" and "Other Supply Sector." "Other Demand Sector" consists of all the other energy demand sectors, that is, the commercial, industrial, agricultural, and transport sectors. The "Other Supply Sector" consists of the energy demand from the auxiliary fuel requirement in the supply sector.

3.2 Commercial sector Sankey diagram

The commercial/institutional sector involves activities related to trade, finance, real estate, public administration, education, and commercial services. For our model, these activities were further divided into offices, retail trade, educational, health care services, accommodation and food services, transportation and warehousing, entertainment and recreation, information and cultural industries, and other services [5]. The majority of the commercial sector energy end use (about 70%) is in the offices, retail trade, and educational services [5]. The final useful energy (118.5 PJ) in the commercial sector is divided into seven major categories and energy use share (%):

- Lighting (refers to lighting inside buildings) (9% of 118.5 PJ)
- Street lighting (0.5%)
- Space heating (60%)

- Water heating (10%)
- Auxiliary equipment (11%)
- Auxiliary motors (8%)
- Space cooling (1%)

In 2009 the total energy input in the commercial sector was 186 PJ [19]; out of this, 118.5 PJ were useful energy. Natural gas and electricity are the primary fuels used in the commercial sector, followed by oil products. As in the residential sector, most of the energy end-use demand (60%) was for space heating.

The model estimated total electricity used in lighting and street lighting is 17 PJ and 1 PJ, respectively. The end-use energy demand efficiency analysis for lighting in the commercial sector is similar to that carried out for the residential sector. The useful energy for lighting was assessed mainly for existing (inefficient) incandescent bulbs, which are slowly being replaced by florescent, CFL, and halogen bulbs. The total energy demand for lighting (not including street lighting) in the commercial sector was 17 PJ in 2009.

Figure 2 is a Sankey diagram illustrating overall energy demand in Alberta's commercial sector. It shows that of the energy required for lighting in the commercial sector, 5 PJ are useful and 12 PJ are rejected. Street lighting has a total electricity demand of 1 PJ with useful and rejected energy of0.3 and 0.7 PJ, respectively.

The total energy demand for space heating in Alberta's commercial sector was 110 PJ in 2009.The *LEAP* model output for water heating and space cooling had total energy demands of 19 and 2 PJ, respectively.

System efficiency for space heating and cooling was evaluated using the weighted average efficiencies of the heating/cooling equipment and the losses from the building. The efficiency of space heating and cooling is assumed to be 60% [36]. For Alberta, the main fuel for water heating is natural gas, and an efficiency of 80% is assumed [5].

Table 2 shows space heating/cooling and water heating energy consumption in the commercial sector for the year 2009. For space heating in the commercial sector in 2009, the useful energy was 67 PJ and the rejected energy was 44 PJ. For space cooling, the useful energy and rejected energy were estimated to be 1.2 and 0.8 PJ, respectively. The useful and rejected energy for water heating were estimated to be15 and 4 PJ, respectively.

Auxiliary equipment in the commercial sector consists of all the computers, computer servers, printers, domestic appliances, industrial washers and dryers, industrial food appliances, medical appliances, vending machines, and similar equipment used in this sector. The auxiliary equipment total energy consumption was 21 PJ (electricity 19, biomass 1 and natural gas 1 PJ) in 2009. The model estimated total electricity consumption of auxiliary motors was 15 PJ. Collectively, the auxiliary equipment in Alberta's commercial sector is estimated to have an efficiency of 80-85% according to the Office of Energy Efficiency (OEE), Natural Resources Canada [5]. In 2009, the total useful and rejected energy for auxiliary equipment was 16 and 4 PJ, respectively.

Auxiliary motors in the commercial sector are assumed to be 90% efficient [36]. The total useful and rejected energy for auxiliary motors was 14 and 1 PJ for 2009, respectively.

[Figure 2]

3.3 Industrial sector Sankey diagram

The industrial sector is the largest energy user in Alberta; it accounts for about 50% of the total energy demand (as shown in Figure 3). Energy end-use analysis for the industrial sector is based on energy intensity as a function of gross domestic product (GDP) (or MJ/GDP).

[Figure 3]

The industrial sector in Alberta includes the following subsectors:

- Construction industry
- Chemical industry
- Other manufacturing
- Petroleum refining
- Mining
- Forestry
- Pulp and paper
- Cement

The 2009 energy demand for Alberta's industrial sector is detailed in Table 3. Biomasses used in the paper and pulp industry are mainly wood chips, saw dust and black liquor. Waste heat used from various industries in the form of steam. The largest energy end use is in the mining subsector, followed by the chemical industry and the pulp and paper industry as shown in Figure 4.

[Figure 4]

[Figure 5]

In the industrial sector, energy is used mainly to produce heat and generate steam or as a source of motive power to fuel boilers for steam and to power motors for pumps and fans. The primary fuels used for these end users are coal, natural gas, oil, and electricity [5]. About 43% of the total energy demand for Alberta's industrial sector was met in 2009 by natural gas (Table 3); this is higher than the individual contributions from all other fuels. Natural gas is followed by oil products and electricity, which contributed 32.8% and 15.7% of the total industrial sector energy demand, respectively. As shown in Table 3, the pulp and paper industry used the most biomass energy, which is predominantly based on the by-products of the pulp and paper industry.

The construction, cement, and other manufacturing subsectors are assumed to have the industrial average efficiency of 80% [36]. However, for mining, petroleum refining, and the chemical industry, the energy end-use fuel demand is higher for process heating and cooling than for other end uses (Table 3).

The total useful energy in the construction industry is estimated to be 9 PJ and the rejected energy to be 2 PJ, as shown in Figure 5. In the other manufacturing subsectors, the total useful and rejected energy are estimated to be 42 PJ and 11 PJ, respectively. In the petroleum refining industry, based on the type of fuel and its corresponding processing efficiency, the useful and rejected energy are 49 PJ and 16 PJ, respectively. In the forestry subsector the useful and rejected energy amounts are 0.7 PJ and 0.3 PJ, respectively. The efficiency is estimated to be about 70% (which is lower than the industry average in Canada); this is perhaps due mainly to the use of diesel oil in the machinery and other equipment.

Alberta's mining industry consists mainly of production from the oil sands, coal, limestone, salt, shale, dimension stone, ammonite shell, sandstone, sand, and gravel [4]. The high energy intensity of the mining industry is largely due to the high energy use in the oil sands; the oil sands sector is therefore the main driver of this sector's high energy demand [5]. The efficiency in the mining subsector is related to energy losses that occur in the operations of the oil and gas industry; which are driven by the process of crude bitumen extraction. Heat is lost in oil sands operations through flue gases and reservoir operating conditions that give rise to heat loss; there are also losses due to low air cooler operating efficiency. The average systemic efficiency in mining sector is estimated at 60%, so there is a large scope for reducing energy intensity [38]. The useful and rejected energy for the mining subsector are 307 PJ and 205 PJ, respectively (Figure 6).

[Figure 6]

3.4 Transport sector Sankey diagram

The transport sector consists of subsectors for transporting passengers and freight; these subsectors are further divided by mode of transport: road, rail, and air. The end-use energy intensities in the transport sector were developed on the basis of passenger-km and freight-km for the passenger and freight transport subsectors, respectively.

The energy end-use demand in Alberta's transport sector is classified into six major subsectors [35].

- Passenger road
- Freight road
- Passenger rail
- Freight rail
- Passenger air
- Freight air

As per the estimates from *LEAP*, the road subsector has the largest end-use energy demand and it is about 83%. Railway and air consume about 8% and 9% respectively. The fuels used include motor gasoline, diesel fuel oil, electricity, natural gas, and some propane (as shown in Table 4). Motor gasoline and diesel fuel oil are the main fuels used in and account for 90% of the total energy used. Gasoline and diesel have an equal share of end use.

The energy intensity of the transport sector depends largely on the type of fuel used and what is being transported (i.e., passenger or freight). For passenger transport, the energy intensity is defined as the amount of energy required to move one person one km. According to the Office of Energy Efficiency (OEE) of Natural Resources Canada, energy intensity depends on fuel efficiency [39]. Average fuel efficiency can be measured in terms of liters of fuel used per 100 kilometers (L/100km), and the total useful energy for a vehicle is calculated based on the losses incurred in driving 100 km. About 14-26% of the energy put into the vehicle is used in moving it; the remaining energy is lost due to engine and driveline inefficiency [40]. Diesel vehicles are becoming increasingly popular because they are 30% more efficient than their gasoline counterparts [41]. In addition to fuel efficiency, there are many factors that affect fuel economy – the method of acceleration, braking, idling time, and driving speed [41]. Fuel efficiency in Canada improved from about 17 to 37% between 1990 and 2008 for passenger transport [39]. However, an increase in the number of light trucks – vehicles with higher energy intensity than cars – has contributed to an increase in the energy intensity of passenger road transportation. Freight trucks have lower mileages and are less fuel efficient than passenger vehicles; consequently, the energy intensity in the road subsector is high.

In order to perform the useful and rejected energy analysis for Alberta's transport sector, the overall efficiencies used are the weighted average of the efficiency of gasoline and diesel vehicles. Weight factor is calculated based on total diesel and gasoline used considering their efficiency divided by input total diesel and gasoline.

These values are adjusted for higher or lower efficiencies depending on passenger or freight vehicle end-use and vehicle mile travelled. The details are shown in Table 5.

The overall supply and demand Sankey diagram for the transport sector is shown in Figure 7. The total energy demand is 398 PJ. The total energy demand in the passenger road subsector is 137 PJ, of which the useful energy is 35 PJ. For the freight road subsector, the total useful energy is 40 PJ and the rejected energy is 151 PJ. For rail and air, the total useful energy is 11.3 PJ and 9.2 PJ, respectively.

[Figure 7]

3.5 Agriculture sector Sankey diagram

Energy intensity in the agriculture sector is defined in terms of MJ per GDP. Energy consumption was estimated for various end uses including direct and indirect operations. Among the fuels, the highest demand is for diesel fuel oil followed by motor gasoline. The details of the fuel use and percentage share based on the *LEAP* model are given in Table 6.

An energy intensity analysis of an agricultural farm considers the type of the fuel used and the end-use operation. End uses for various farm operations energy use shares are; truck and auto (18%), heat and light (11%), farm M/C (51%), non-farm (18%) and other (2%) [39; 42].

The Sankey diagram for energy use in the agricultural sector is given in Figure 8. The total estimated useful energy is 29 PJ out of a total energy input of 50 PJ in the year 2009. The greatest end-use energy demand is for oil products, which constitute 38 PJ of the total end-use energy in Alberta’s agricultural sector.

[Figure 8]

4. Supply Side Sankey Diagrams

Alberta’s supply sector was modeled under the transformation module in *LEAP* which consists of the following key branch modules [33]:

- Electricity generation
- Natural gas and coal-bed methane
- Alberta oil refining
- Crude oil production
- Synthetic crude oil production
- Crude bitumen production
- NGL production
- Coal mining

4.1 Electricity generation – Sankey diagram

Electricity generation is the subject of one of the critical transformation modules for the province of Alberta. Alberta‘s electricity generation mix consists of coal, natural gas, oil, and renewables. This mix consists of conversion technologies based on different primary fuels such as coal, natural gas, oil, and some renewables (hydro, wind, and biomass).

Electricity production from power plants takes into account total demand as well as transmission losses. The input energy data are shown in Table 7. Details on the electricity modules and their characteristics are given in an earlier study [33]. The total energy input to Alberta's grid, as estimated by the *LEAP* model, is about 645 PJ. The overall Alberta's electricity generation – energy output is estimated at 239 PJ (Table 8).

Electricity generation efficiency is based on the Alberta Electricity System Operator's (AESO) assessment and data from various provincial reports. The electricity generation efficiencies of different power plants in Alberta are also given in Table 8. The overall Sankey diagram for Alberta's electricity generation sector is shown in Figure 9.

[Figure 9]

4.2 Other supply sector Sankey diagrams

The other supply sectors consist of energy supply in Alberta's oil and gas sectors. These sectors are shown as separate branches in all the Sankey diagrams, and the diagrams show detailed total end-use data as well as auxiliary fuel requirements for the energy supply sector. The auxiliary fuel requirement for all the supply sectors is a parasitic power requirement and hence is shown as a separate demand branch for the supply sectors.

4.3 Benefits of Sankey Diagrams

These diagrams represent the energy flows in different energy demand and supply sectors. These diagrams help in understanding the extent of energy use and efficiency of energy use in different energy sectors. The information from these diagrams helps in identifying the sectors which have energy use and the type of energy use. It also helps in identifying the sectors which have potential of improvement of energy use efficiency. This can further help in development of options for achieving high energy use efficiency. These information helps in identifying the areas in which the policy formulation is needed so that the energy use efficiency can be improved.

5. Conclusion

The energy flow from fuel to end use was mapped for Alberta's five energy demand sectors, residential, commercial, transportation, industrial, and agricultural. The Sankey diagrams show total energy consumption, useful and rejected energy, and energy intensities of various end-use devices. In both the residential and commercial sectors, the highest energy consumption was for space heating in which the total useful energy and rejected energy were 76 PJ and 50 PJ, 67 PJ and 44 PJ, respectively. In the industrial sector, the highest energy was consumed by the mining subsector, where 307 PJ of energy was used and 205 PJ rejected. The freight road subsector consumed the highest energy of all the subsectors in the transportation sector; very low end-use (vehicle) efficiency was found, with useful and rejected energies being 40 PJ and 151 PJ out of 191 PJ of total input energy. In the agriculture sector, the useful and rejected energies were 29 PJ and 21 PJ, respectively.

On the supply side, the subcritical coal plants showed the highest energy transactions with a total input energy of 350 PJ out of which the useful energy was only 105 PJ, indicating very low efficiency. Supply side energy flow was studied for electricity generation and various auxiliary fuels.

The majority of end-use energy in the residential and commercial sectors is used for lighting, space heating, and running appliances/equipment and motors, whereas in the industrial and agricultural sectors, end-use energy is used for process heating and for running electrical equipment and both motive and non-motive equipment. In the transportation sector, where the largest amount of energy is consumed, energy is used in passenger and freight vehicles, and energy use was considered according to different modes of transportation, e.g., road, rail, and air. The average energy efficiency or energy intensity of a particular type of end-use operation or equipment determines the existing useful energy, and inefficiencies contribute to the rejected energy. Overall sectoral energy end use was assessed and further separated into estimates of useful and rejected energy.

This analysis will provide a framework for efficient energy accounting. It gives a physical description of energy systems and helps in estimating GHG abatement potential, the costs associated with the energy systems, and other environmental impacts. The purpose of the Sankey diagrams is twofold: first, to give an understanding of high-, medium- and low-energy efficiency systems in the energy profile of demand and supply sectors; and second, to project the gap between the actual achievable useful energy and the existing energy profile of a given sector or subsector. This difference between the existing and the achievable energy profile will serve as a basis for further evaluation of efficiency improvement options.

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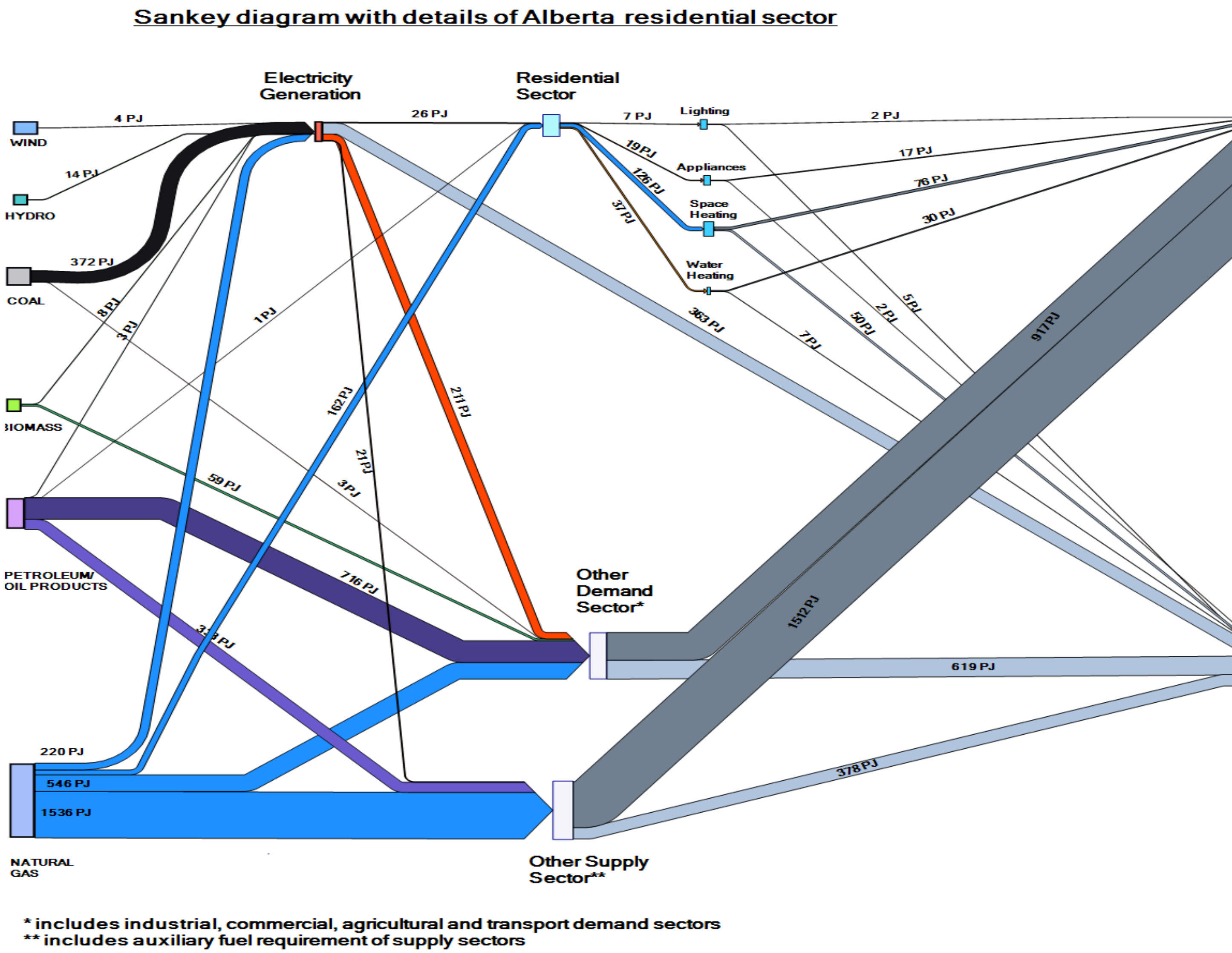


Figure 1: Energy supply and demand Sankey diagram for Alberta's residential sector for 2009

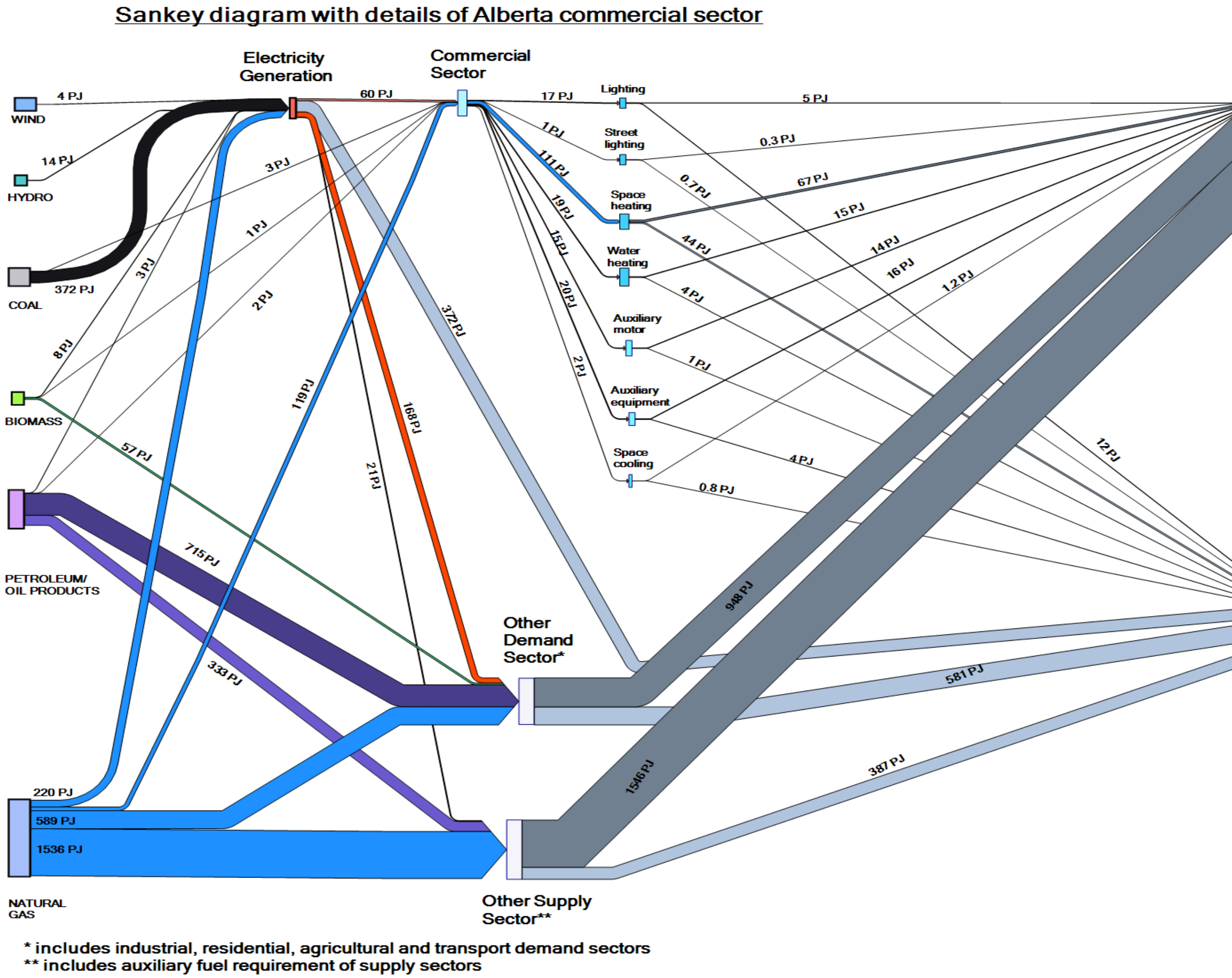


Figure 2: Overall energy supply and demand Sankey diagram for Alberta's commercial sector for 2009

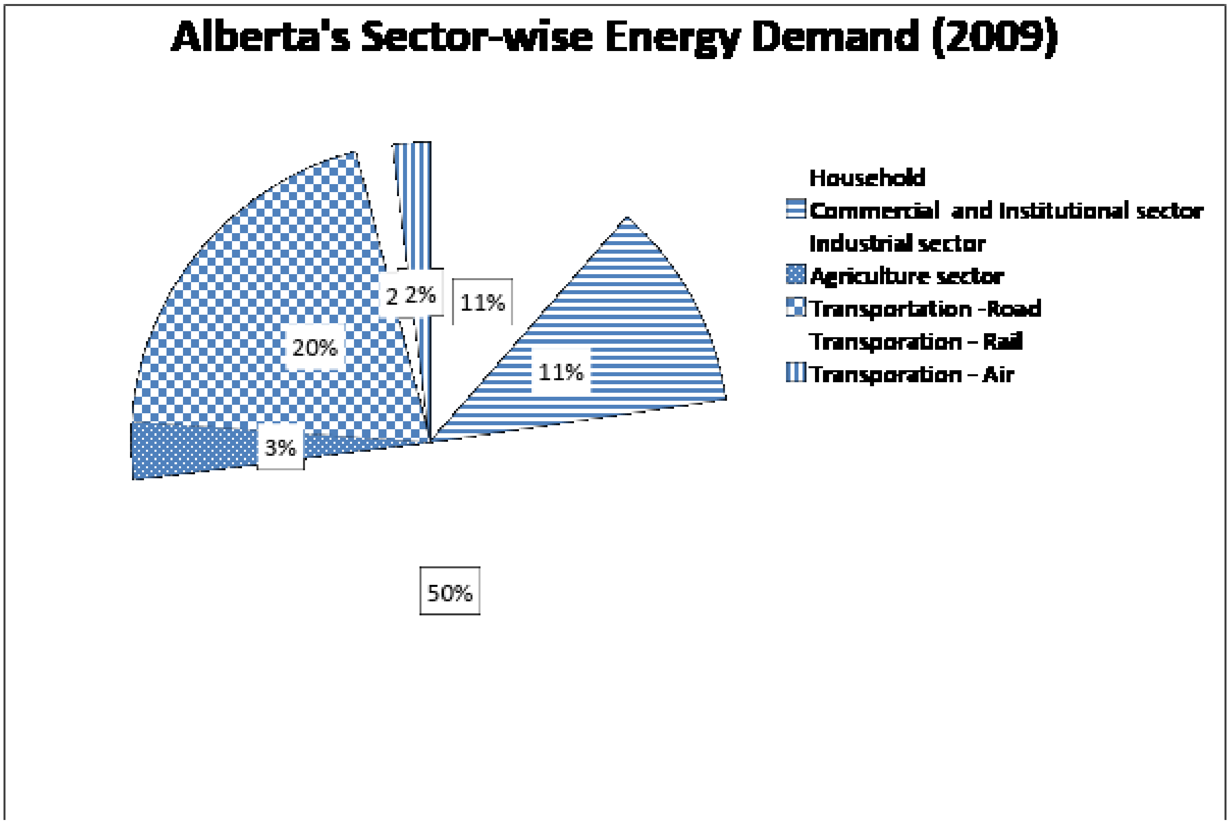


Figure 3: Alberta's energy demand sectors as developed by the *LEAP* model

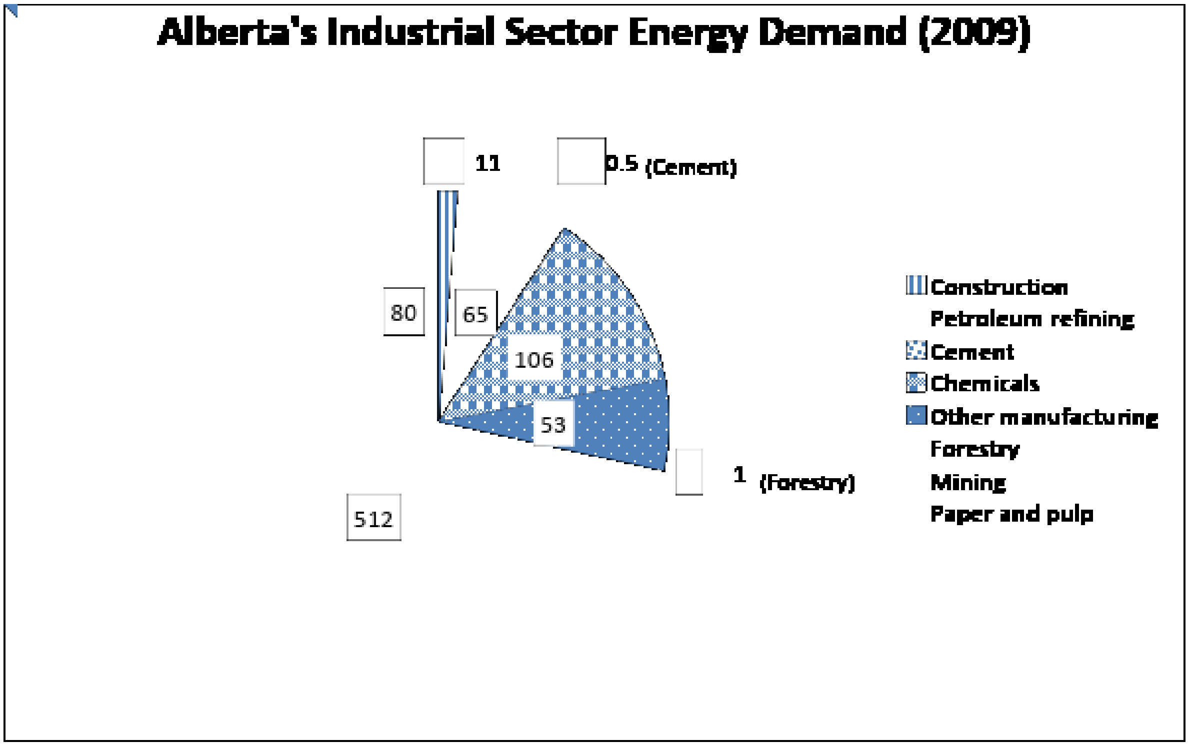


Figure 4: Alberta's industrial sector energy demand for 2009 as estimated by the *LEAP* model

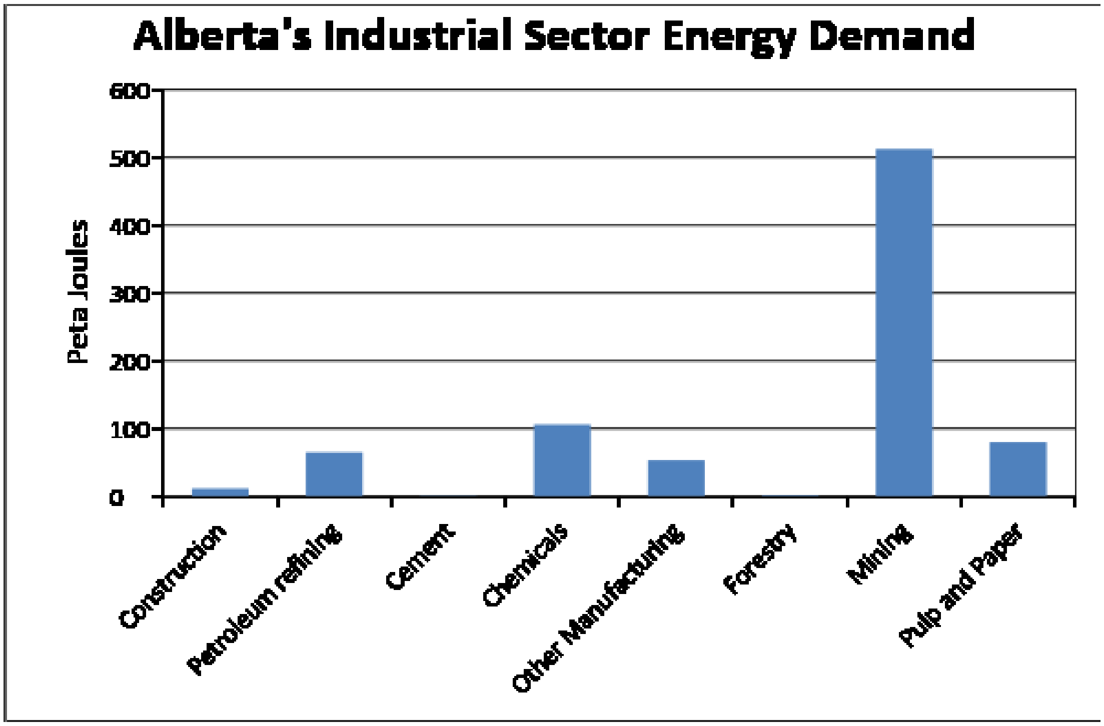


Figure 5: Alberta's industrial sector energy demand for 2009 as estimated by the *LEAP* model

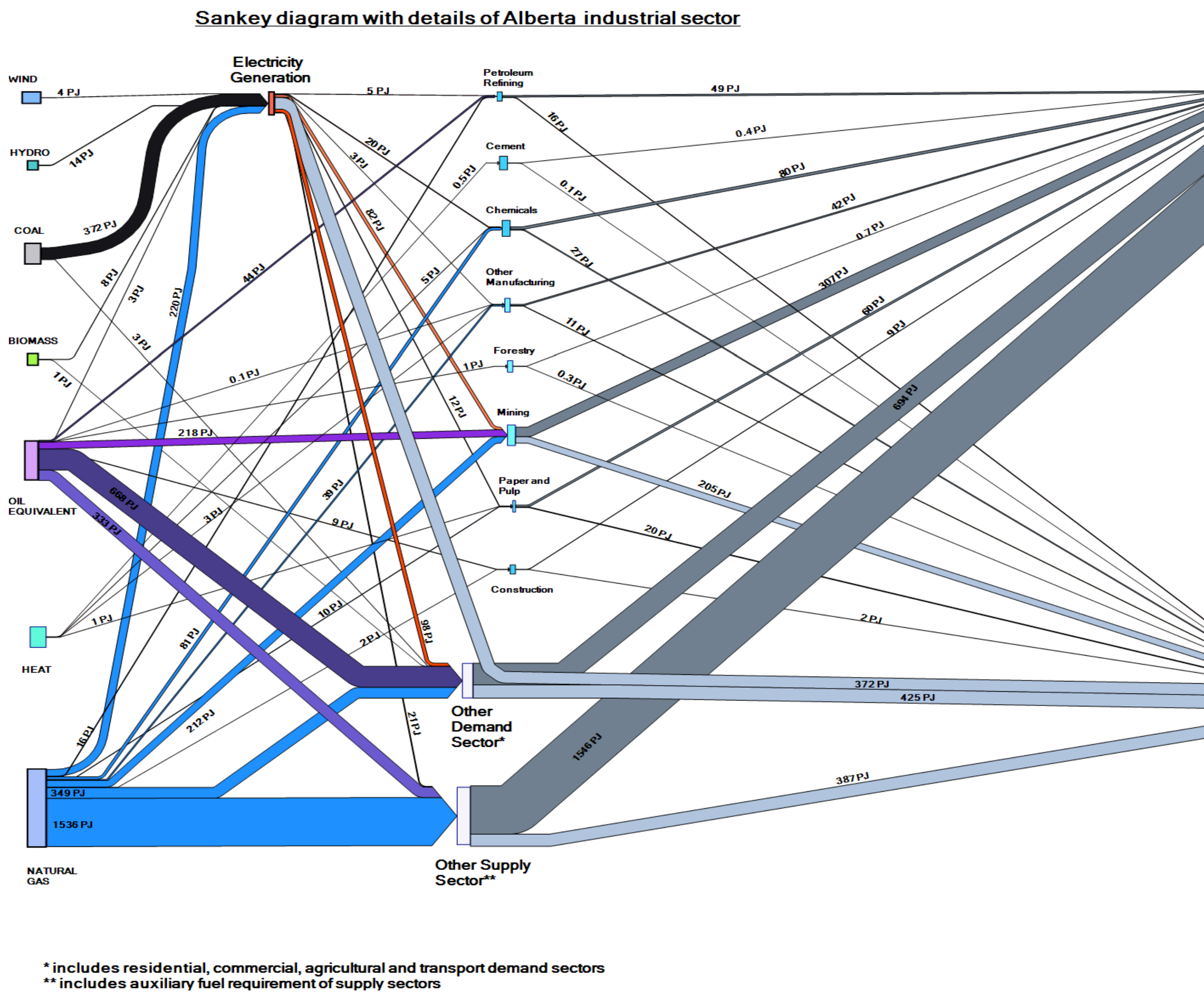


Figure 6: Overall energy supply and demand Sankey diagram for Alberta's industrial sector for 2009

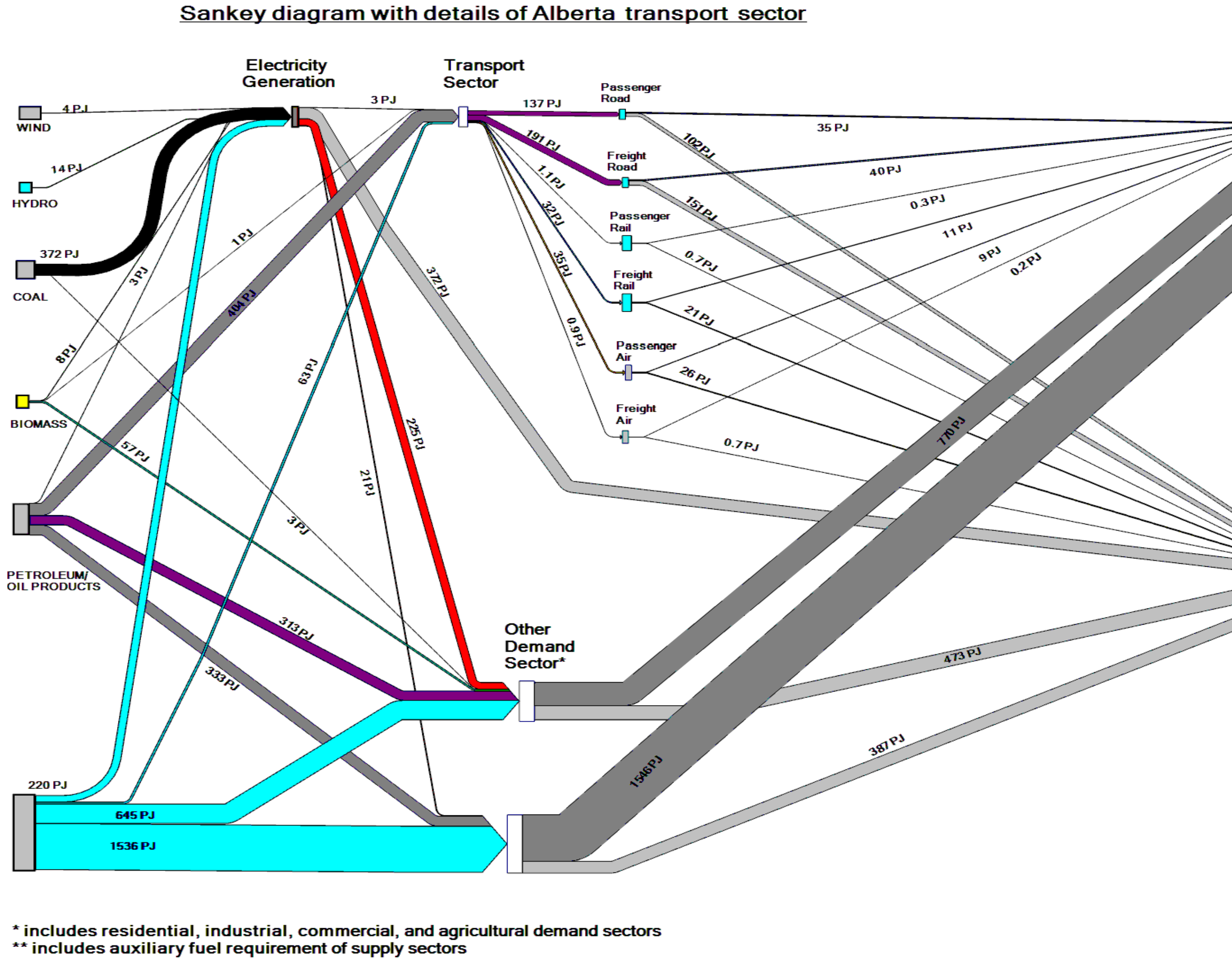


Figure 7: Overall energy supply and demand Sankey diagram for Alberta's transport sector for 2009

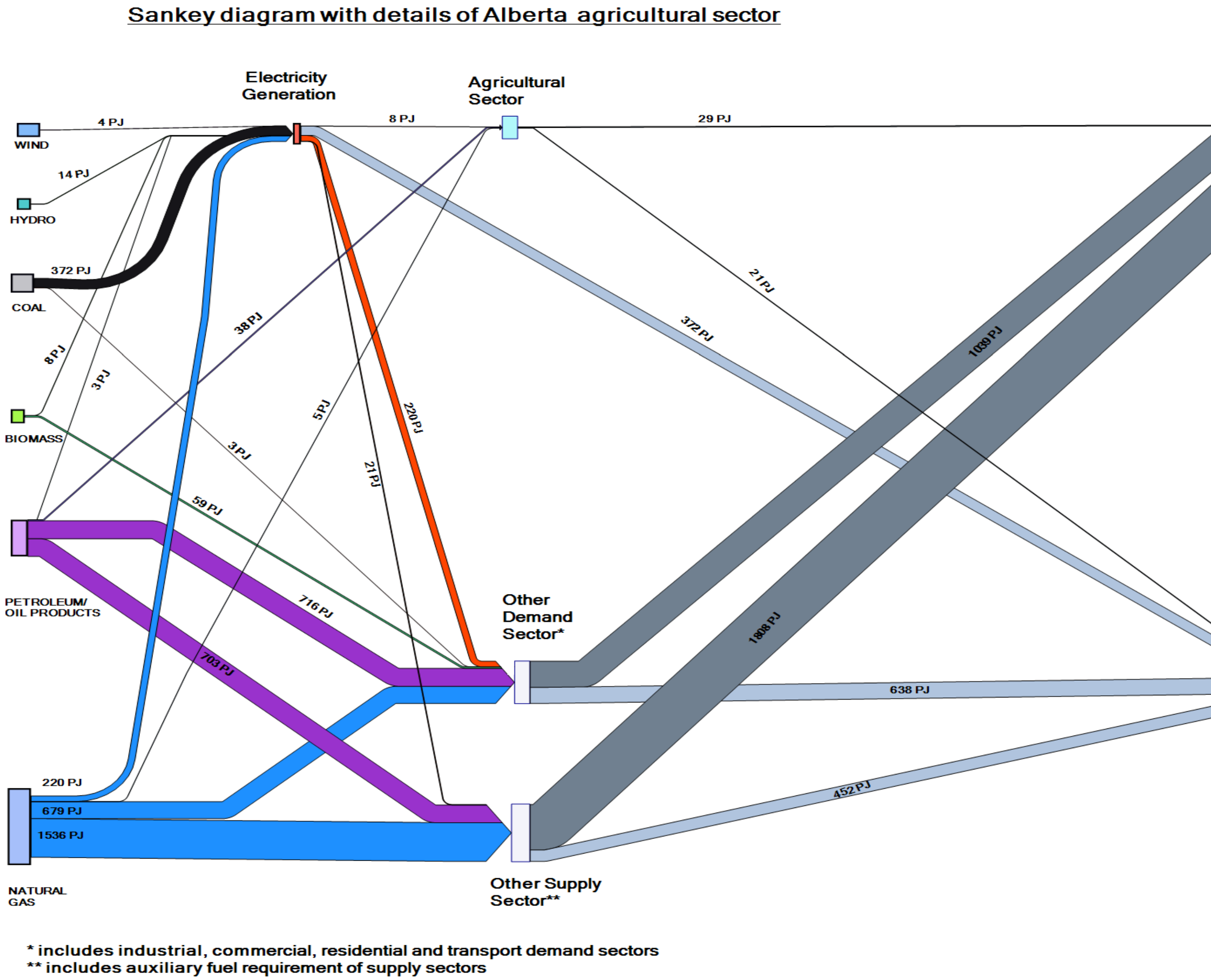
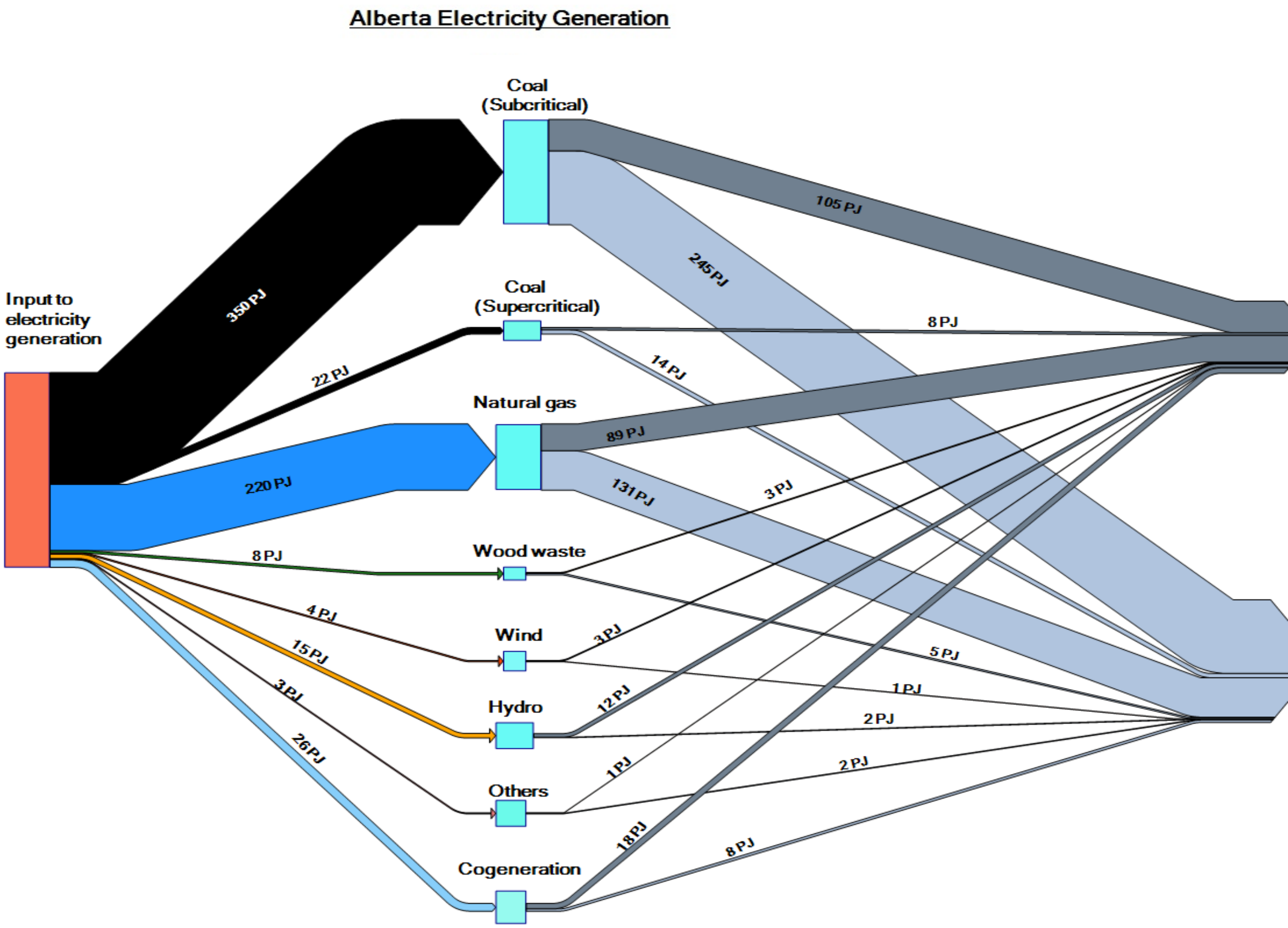


Figure 8: Overall energy supply and demand Sankey diagram for Alberta's agriculture sector for 2009



* excludes the useful energy of 19 PJ for auxiliary power requirement
** includes T&D (transmission and distribution) losses

Figure 9: Overall electricity generation sector Sankey diagram for Alberta for 2009

Table 1: Alberta's energy demand sectors basic assumptions for the base year 2005 [28-30]

Sector	Characteristic	
Residential	No of households - 1.23 million households (size of each household is 3 persons)	
Commercial and institutional	Total square area - 93.9 million sq. m.	
Industrial	GDP based on type of industry (million CDN $)	
	Construction	11.5
	Smelting &refining	0.1
	Petroleum refining	0.2
	Cement	0.1
	Chemicals	2.3
	Iron and steel	0.1
	Other manufacturing	10.7
	Forestry	0.5
	Mining	20.8
	Paper and pulp	0.5
	Total	46.7
Agriculture	GDP- 3.23 million (CDN)	
Transport	Passenger Km: 17728 and Freight Km: 17186	
Other sectors.	Total energy consumed ● Pipeline transport-63 PJ ● Non energy demand-331 PJ ● NG reprocessing and shrinkage-200PJ	

Table 2: Commercial sector energy demand for space heating/cooling and water heating in PJ for 2009

Commercial sector end use	Biomass	Electricity	Heat	Natural gas	Oil products	Solid fuels	Total
Space heating	0	5	0	101	1	3	110
Water heating	1	1	0	17	0.2	0	19.2
Space cooling	0	2	0	0	0	0	2

Table3: Industrial sector energy end use by primary energy (PJ) and efficiency

Industrial sector (PJ)	Biomass	Electricity	Heat	Natural Gas	Oil Products	Total	Efficiency of end-user/sub sector
Construction	0	0	0	2	9	11	80%
Petroleum refining	0	5	0	16	44	65	75%
Cement	0	0	0.5	0	0	0.5	80%
Chemicals	0	20	5	81	0	106	75%
Other Manufacturing	0	11	3	39	0.1	53	80%
Forestry	0	0	0	0	1	1	70%
Mining	0	82	0	212	218	512	60%
Pulp and Paper	57	12	1	10	0	80	75%
Total	57	130	9.5	360	272	828.5	

Table 4: Alberta's transport sector energy end use of different fuels in 2009 (PJ) as estimated by the *LEAP* model

Mode of Transport	Gasoline	Diesel	Electricity	Natural gas	Propane	Aviation gasoline	Aviation turbo	Total
Road	179.4	145.9	0.6	0.1	1.6	0	0	328
Rail		32.8						33
Air						0.63	34.62	35
Percentage of total (%)	45.34	45.17	0.15	0.03	0.40	0.16	8.75	100

Table 5: Transportation sector end-use energy demand

Road - Type of Fuel	Total energy (PJ)	Freight Efficiency (%)	Weighted Average	Total energy (PJ)	Passenger Efficiency (%)	Weighted Average
Diesel	135.8	23		10.1	35	
Gasoline	54.2	15		125.2	25	
Total	190.9		21%	136.7		26%

Table 6: Total energy demand for various fuel types and share in Alberta's agriculture sector for 2009 as estimated by *LEAP*

Agriculture sector	Energy demand (PJ)	Share (%)
Electricity	8.33	16.4
Natural gas	4.63	9.1
Diesel fuel oil	23.50	46.2
Motor gasoline	14.16	27.9
Propane	0.21	0.4
Total	50.83	100

Table 7: Alberta's electricity generation- input energy

Electricity generation (2009)	Input (PJ)
Biomass	8.11
Coal	372.37
Electricity (auxiliary fuel requirement)	23.76
Heat	0
Hydropower	14.06
Natural Gas	219.68
Nuclear	0
Oil Products	3.26
Renewables	3.6
Total	644.84

Table 8: Alberta's electricity generation - output energy and plants efficiency

Electricity Generation (2009)	Output (PJ)	Efficiency (%)
Coal-fired generation	105	33
Cogeneration electricity surplus from oil sands	18	80
Gas-fired generation	89	50
Hydro	12	90
Other*	1	37
Supercritical coal plant	8	39
Wind	3	90
Wood waste	3	36
Total	239	-

*Other category includes power generation plants based on municipal solid waste, residual fuel oil, and miscellaneous feedstock not listed in the other subsectors.