Energy Conversion and Management 91 (2015) 342–352

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Using Sankey diagrams to map energy flow from primary fuel to end use

Veena Subramanyam, Deepak Paramshivan, Amit Kumar *, Md. Alam Hossain Mondal

Department of Mechanical Engineering, 4-9 Mechanical Engineering Building, University of Alberta, Edmonton, Alberta T6G 2G8, Canada

ARTICLE INFO

Article history:
Received 8 July 2014
Accepted 9 December 2014
Available online 27 December 2014

Keywords:
Energy flows
LEAP model
Sankey diagrams
Energy sectors
Alberta
Canada

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 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 Energy Alternatives Planning System (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.

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

* Corresponding author. Tel.: +1 780 492 7797; fax: +1 780 492 2200.
E-mail address: Amit.Kumar@ualberta.ca (A. Kumar).

http://dx.doi.org/10.1016/j.enconman.2014.12.024
0196-8904/

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 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, and heating. 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 to 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