A Sankey Framework for Energy and Exergy Flows[1]

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Abstract

Energy flow diagrams in the form of Sankey diagrams have been identified as a useful tool in energy management and performance improvement. However there is a lack of understanding on how such diagrams should be designed and developed for different applications and objectives. At the national level, matching various features of Sankey diagrams with the various objectives of energy performance management provides a framework for better understanding how Sankey diagrams can be designed for national level analysis. As part of the framework, boundaries outlined around a group of facilities provide a refined representation of sub-systems that trace energy use in various conversion devices, products and services. Such a representation identifies potential areas for energy savings; an important objective of energy performance management. However, Sankey diagrams based on energy balance falls short in effectively meeting this objective. Sankey diagrams based on exergy balance on the other hand provide unique advantages in identifying potential areas for energy savings. This is illustrated at a facility level, using the example of a LNG regasification facility that overlays both energy and exergy flow diagrams.

Keywords: Sankey diagrams, national level energy analysis, energy stages, energy flows, energy savings, exergy balance

1. Introduction

Sankey diagrams have been used as an effective tool to focus on energy flow and its distribution across various energy systems. It is represented by arrows, where the width of which represents the magnitude of the flow. Mario Schmidt presented a comprehensive review of the historical uses of Sankey diagrams stressing its rising importance in decision making and public policy [1]. For example, the use of Sankey diagrams for identifying energy efficiency improvements *for a society* was addressed in 1971[2]. Many countries and international agencies have represented energy flows using Sankey diagrams from supply to end use sectors. International organizations such as ISO have developed energy management systems standards such as ISO 50001 (Energy Management Systems) to improve organizational energy performance. ISO 50001 recognizes the Sankey diagram as one of the tools that could be used in the energy review process that involves analyzing consumption, identifying significant consumption and identifying areas for improvements for energy performance planning [3]. However, there is a lack of understanding on how such Sankey diagrams should be designed and developed for different applications and objectives. Issues such as the diagram's structure (e.g. should flows be centred on processes, physical equipment, final energy services or a combination of these) and the appropriate level of detail and granularity are not fully addressed.

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In addition, energy analysis does not support assessment of the quality and usefulness of energy. On the other hand, exergy analysis of energy systems and processes serves as a quantitative measure of quality and usefulness of energy [4]. Therefore, Sankey diagrams that represent exergy flows can be very useful in identifying thermodynamic losses and potential areas for energy savings, and providing a rational basis energy performance benchmarking, and for improving energy management systems and activities.

2. Literature Review of Sankey Diagrams at National Level

Although Sankey diagrams were originally developed to trace energy flows for steam engines, its application to energy flows in a society (e.g. at national and global level) has become increasingly important in recent years. A review of the use of Sankey diagrams at the national level has been conducted, to identify and understand the features and differences of these Sankey diagrams.

Some of the key features and differences of Sankey diagrams identified through this review include *system boundaries* (both spatial and temporal), *level of granularity*, and *representation of energy loss*.

2.1 System boundaries

Energy system boundaries associated with Sankey diagrams include both spatial and temporal boundaries. The spatial boundary is a surface that demarcates a region within which energy activities are being traced and analysed. For most national level Sankey diagrams, the spatial boundary of the energy system is the physical boundary that demarcates the countries within. With such a boundary defined, the inflows are termed imports and the outflows are termed exports [5]–[7].Spatial boundaries suitable for national level analysis can also be created for an aggregation of energy components and facilities within the same economic sector or activity, for example, the power generation sector, refining sector, industrial sector, transport sector, household sector, and building sector. For example, the US Department of Energy (USDOE) has analysed the U.S industrial sector as an energy system characterising electricity inflows as offsite generation and outflows as electricity exports from that sector [8]. Lawrence Livermore National Laboratories (LLNL) has been producing Sankey diagrams that analyse the energy flow in the United States since 1976. In the most recent energy flow representation, the boundary of the energy system is defined to focus on the consumption of energy, without differentiating between imports, exports and local production of energy.

Temporal system boundaries refer to the time period for which the Sankey diagram has been developed. For example, early Sankey diagrams were often a steady state “snapshot” of energy flows, such as for a steam engine. Therefore, they represent energy flow rates (or power) rather than energy flows. At the national level, energy flows in Sankey diagrams are typically aggregated for a particular time period, typically one year. Depending on the time period selected, different representations of fuel stocks (typically for analysis of longer time periods) and energy storage (typically for shorter term analysis) will be useful.

2.2 Level of granularity

The level of granularity in a Sankey diagram refers to the extent an energy system is broken down (disaggregated) or refined. This is characterised by the definition and representation of *energy stages* and *energy flows* in the diagram.

2.2.1 Energy stages

Energy stages describe which segments of the energy flowing in the system are to be traced. In most national-level Sankey diagrams reviewed (see Figure 1), three main stages are broadly identified: *primary energy supply*, *energy transformation* and *energy consumption* (or end-use demand), and these are essentially "verticals" within the Sankey diagram.

The primary *energy supply* stage represents the various primary energy resources that enter the boundaries of an energy system, and can also be described as the utilised energy resources within the energy system. The primary supply of energy is usually classified into various types of fossil fuels and renewables, and to different levels of detail (e.g. some show only coal as one category, while others differentiate between different coal types, such as lignite and bituminous coal). Sometimes, the supply stage is further divided into sub-stages comprising *raw resources* (e.g. petroleum in oil fields), *resource extraction/production* (e.g. in oil production platforms) and *resource transportation* (e.g. using oil tankers or pipelines) [9].

The *energy transformation* stage broadly refers to energy resources being converted to energy carriers and secondary forms of energy supply including electricity, various types of fuels, and various forms of thermal energy carriers (e.g. steam and chilled water). Oil refineries, power plants, and district energy (heating or cooling) systems are examples of facilities/components within the energy transformation stage. However, some Sankey diagrams do not differentiate between primary resources and their associated carriers, [10], [11], effectively combining the supply and transformation stages. Such a representation for oil-related energy flows would not differentiate between flows of *crude oil/petroleum*, and flows of *petroleum products* such as diesel and gasoline [6]. Other diagrams represent oil refineries as part of the industrial sector in the (end use) consumption stage [11]. Some diagrams include a *transmission and distribution* sub-stage that represents the delivery of energy to the consumption stage via energy carriers, and could include facilities such as transformers and electrical substations. Blurring of supply and transformation stages is more evident when alternative energy flows are represented. Alternative energy transformation technologies such as wind farms, hydroelectric power stations and solar photovoltaic systems are located close to where resources are utilized. Thus supply of energy usually starts with the electricity generated from such alternative energy transformation sectors [5], [11], [12].

The *energy consumption stage* incorporates the various activities and flows associated with final energy use and consumption to provide desired *energy services* to the energy user who uses them to produce useful products and services. The consumption stage often incorporates sub-stage representations of *end-use energy conversion* (e.g. in energy consuming devices/equipment such as boilers, lighting devices, motors and chillers), *demand sectors* (e.g. transport, commercial, residential and industry sectors and sometimes important energy-intensive sub-sectors such as cement production, petrochemicals, iron and steel, water and waste), and various *energy services* (such as transportation, lighting, space and process heating and cooling) to better represent the energy use associated with various activities within the consumption stage. In some cases, energy services are categorized according to the final manufactured products or commercial services that are delivered, and can be viewed as further sub-division of the demand sectors and sub-sectors described earlier. Within the energy consumption stage, a distinction between devices which convert energy into useful forms and "passive systems" that transform energy into final services has been proposed by Cullen and Allwood [10]. Efforts have also been made to map final energy services further to their respective demand drivers [13]. Further research and analysis is needed to determine if these proposed refinements are indeed useful towards different possible application and objectives of national level Sankey diagrams. It is also important to note that most energy flow representations at the consumption stage are usually limited by the amount of reliable data available. Enhanced methods of data collection (e.g. use of smart meters) can make such refinements to energy consumption representation more effective.

Green	Primary Supply Stage
Red	Transformation Stage
Blue	Consumption Stage

Source Date Published	Boundary Metric Year of Data	Energy Stages
Ma et al 2009 [7]	China Energy (100 mtoe) 2006	Primary energy supply (including import / export) → Primary energy transformation (power stations and oil refineries) → Secondary energy supply (including import / export) → End-Use Sector (transportation and other sectors)
Statistics Canada 2011[6]	Canada Energy (PJ) 2009	Primary and secondary energy supply (including import / export) → End-use sectors (residential, commercial, industrial, transportation, non energy use, transformations and producer consumption)
LLNL 2012 [11]	US Consumption Energy Quads 2011	Primary and secondary energy consumption → Energy transformation (electricity generation) → End-use sectors → Energy Services and Rejected Energy
Ma, Fu, et al. 2012 [9]	China Energy, Oil (Mt) 2009	Primary supply (including imports and exports) → Oil refinery → Secondary supply (including imports and exports) → Final sectors (including transportation , power & heat, building and factory) → End use in transportation and factory sectors
DECC 2012 [5]	U.K. Energy (Mtoe) 2011	Primary and secondary energy supply (including import, export and bunkering) → Energy transformation (power stations and oil refineries) → End-use sectors (including transport, iron & steel, other industry and domestic)
Sims and Schock 2007 [14]	Global Energy (EJ) 2004	Supply Resources → Primary energy supply → Primary energy transformation (power stations) → End-use sectors (including buildings, industry, transport)
USDOE 2009 [8]	US Industrial Sector Energy (Tbtu) 2006	Supply (Including onsite and offsite supplies) → Energy End Use (including process energy and non process energy)
Cullen and Allwood 2010 [10]	Global Energy (EJ) 2005	Primary energy supply → End use conversion devices / Electricity Generation → Passive systems/ end-use sectors → Final energy services
IEA 2012[15]	Global Energy (EJ) 2009	Primary energy supply → Energy Transformation (including oil refineries and electricity transformation) → Final sectors → Final energy services and products

Figure 1. Previous work of Sankey representation of energy flow for national level analysis

2.2.2 Energy flows

Energy flows constitute the most basic and important parts of a Sankey diagram, and at the national level, show the relationships and flows from energy resources (primary supply stage) to end use (consumption stage). Most energy flow representations use colour coding and individual labelling of the flows. In some cases, different shades of the same colour are used to distinguish imports from local production of various energy sources.

The representation of import and exports varies across different Sankey diagrams at the supply and transformation stages. Some representations trace the imports and exports of energy resources and carriers branching out at various stages of the energy flow diagram[9]. In other cases, energy imports of resources and carriers (e.g. crude oil and refined oil products imports) are not differentiated and represented together at the supply stage [6]. Other differences in representing energy flows are the representation of storage and stock exchange flows of energy carriers.

2.3 Energy loss representation

Energy losses occur at all three stages described in the previous section. For example, the difference between energy resources leaving the primary supply stage and energy entering the consumption stage would include transport and distribution losses, as well as energy transformation losses. Transport and distribution losses are usually small and only a few Sankey diagrams reviewed represent the losses at this stage [9].

Losses at the transformation stage can also be described as primary energy conversion losses. Primary energy conversion losses (representing the energy that is not converted from fuel to electricity) for centralized thermal power plants are often represented explicitly. For oil refineries, losses are either shown explicitly (typically small compared to losses in power plants) [14] or combined with transport and distribution losses associated with distribution of petroleum products [7], [9], [14].

For alternative/renewable energy, the situation is more complicated. Non-thermal resource flows that are part of renewable energy power plants (e.g. hydropower stations, wind farms and solar panels) are reported in BTU-equivalent values assuming a typical fossil fuel plant "heat rate" [11], although renewable and non-renewable power plants may have different degrees of losses resulting from the conversion process. Losses resulting from conversion of biomass into non electricity carriers (e.g. various forms of liquid or gaseous biofuels and heat) are also not represented in any of the diagrams reviewed. Such variations in energy representations are mainly attributed to the insufficient distinction made between alternative energy resources and their associated energy carriers at the supply and transformation stages respectively.

For many of the national-level Sankey diagrams reviewed, energy losses at the consumption stage are not represented. The diagram developed by LLNL for the USA is an exception, providing estimates of the amount of both useful and rejected energy. At the global level, IEA has published diagrams that indicate losses for the transportation sector and not for the building and industrial sector [16]. USDOE's diagram represented energy losses for the industrial sector where various industrial processes and non-processes are grouped into fifteen end uses that included efficiency estimates derived from published literature and discussions with industry experts. It is clear that energy loss representation within the consumption stage requires further refinement; due to difficulties faced in defining and identifying energy losses and collecting detailed data needed to quantify these losses.

There are several reasons why representing energy losses within the consumption stage are particularly challenging. Firstly, it is difficult to define and identify what is “useful” and what is “lost” in many end use conversion devices. Take the example of a car and a television. For a car, the useful portion of the energy is often taken to be the mechanical output that is used to drive a car, and can be measured and quantified (e.g. by using a dynamometer). For a television the useful energy is not that easily quantified as it comprises energy forms that are difficult to measure such as light and sound, whose “usefulness” are not easily quantified. Secondly, data collected at a national level may not include sufficient information to analyze energy losses, therefore specific surveys may have to be specially conducted for various demand sectors to obtain information making it difficult to align methodologies across all the various end use conversion devices, products and services. Finally, energy losses are also highly dependent on operating equipment and conditions making it challenging to group and represent and quantify various energy losses in a consistent and comparable manner.

3. Sankey Framework for Energy Flow Analysis at National Level

National level analysis of energy systems are often performed under three categories of interests: energy economics, environmental impacts of energy, and energy security. Alternative classification of the objectives of analysis, such as increasing the use of alternative energy, and identifying areas for energy efficiency improvements and energy conservation have ramifications in all three categories mentioned above. These inter-linkages and inter-dependence of objectives make it challenging to develop a useful framework for developing Sankey diagrams for national level analysis. No single Sankey diagram representation is able to fulfill all the objectives of energy analysis at the national level. Instead, alignment of objectives with key features of Sankey diagrams can offer an effective approach to the design and utilization of Sankey diagrams.

Public awareness, security of supply, increasing use of alternative energy, and identifying areas for energy savings are identified as examples of commonly used objectives in national level analysis. Important Sankey diagram features associated with these objectives will be discussed in the following paragraphs. Economic objectives have been intentionally excluded, since the focus of this paper is to analyse how to better represent the *physical* aspects of energy flows through various energy systems. It is important to note that the framework does not suggest a rigid mapping between objectives and key features identified, but suggests that different features are assessed to be particularly useful in meeting different objectives.

Irrespective of objectives, clarity and ease of use are important features of Sankey diagrams that must be present. Therefore, color coding and labeling of energy flows to improve clarity and ease of use should be a feature for all Sankey diagrams.

3.1 Public awareness

Public awareness refers to making the common people aware of energy issues and enhancing their ability to contribute directly to national energy challenges and needs. Thus, tracing of energy flows starting from energy use at the consumption stage (especially for end-use sectors of high public interest such as such as households, buildings and transport sector) is particularly useful for such an objective. Such a representation facilitates the delivery of key messages about energy consumption to the public. Drawing the boundary of the energy system around consumption of energy enables (arguably) less important details such as import and export flows of energy resources, and transport and distribution losses to be avoided. Such a representation reduces the complexity of the energy representation, making the information presented more impactful [11].

To enhance public awareness, it is also useful to provide additional details at the consumption stage, for example, energy flows through end use conversion devices, and how energy is used to produce useful products and services in the relevant consumption sectors.

3.2 Security of supply

The security of supply here refers to the security of domestic supply of energy resources or carriers entering the energy system. Representation of import and export flows of energy resources and carriers; specifically the representation of imports entering energy intensive sectors in both the transformation and consumption stage are crucial at a national level for analyzing and reducing import dependencies. This usually requires energy intensive sectors to be represented separately to improve the clarity in the representation [5]. Another important feature identified is the tracing of alternative energy resources to various energy carriers. This allows for alternative energy pathways to be identified, diversifying the supply mix of energy resources [12]. Other features such as stock exchanges and storage flows provide a more realistic picture of the extent of fossil fuels locally being produced.

3.3 Increasing the use of alternative/renewable energy

Increasing the use of alternative/renewable energy is an important step to reduce carbon emissions, attain a more sustainable energy system and meet other environmental objectives. In order to increase the use of alternative and renewable energy, it is necessary to differentiate between primary energy resources and their associated (secondary energy) carriers. Without differentiating the two types of energy flows, it would not be possible to identify areas where alternative energy resources can be incorporated. Representation of important energy intensive sectors, import and export flows at the transformation or consumption stage identifies areas where alternative energy is currently incorporated. However this may not be sufficient to identify alternative *technology pathways* for alternative energy incorporation. Refining sub-systems provide additional information that could potentially be used to identify such alternative technology energies could be used. For example, a detailed Sankey representation of China's energy transformation process, identified potential areas for hydropower to be used as an alternative for coal powered power generators [7]. In addition to that, upstream conversion losses of non-electricity carriers are not represented in existing Sankey diagrams. Although this may be a small contribution, tracing such conversion processes could possibly identify suitable alternative resources (e.g. the development of advanced biofuels).

Refining representation focused on various consumption sectors provide many opportunities to increase the use of alternative energies in various end use products and services. For example ETP 2012 published energy flows in the form of Sankey diagrams tracing the allocation of energy sources to various end use products and services in the building sector. Although electricity and renewables account for about 60% of total buildings' energy consumption, it can be inferred that there is still much potential for alternative energies in space heating; less than 15% of renewables is used for space heating purposes [16].

Other useful features are the presence of storage flows in energy flow representations which will also have an increasing significance in the future as energy storage solutions become a more viable solution in solving intermittency in renewable energy supplies.

3.4 Identifying areas for energy savings

Energy savings at the national level can be met by two approaches; *energy efficiency improvements* and *energy conservation, each with its own set of needs and characteristics*. Improving energy efficiency generally aims to reduce the supply of energy to meet a desired energy demand, for example, through reducing losses and improving the efficiency of energy conversion devices and processes. On the other hand, energy conservation involves the reduction of energy demand, for example through improving and changing societal, organizational and individual practices and habits.

At the transformation stage, energy efficiency is dependent on the energy transformation technologies that supply secondary energy through various energy carriers. Therefore all key features associated with representing the scale of energy and energy losses flowing through the transformation stage would be important. However, for a given transformation technology (e.g. a steam power plant) there will be limited potential for improvements in energy efficiency, and it is only through the development and use of new and emerging technologies that additional energy efficiency improvements can be realized. Therefore tracing of alternative energy resources to various energy carriers is identified as a key feature since the push to increase the use of alternative energy in turn simulates research and development of new technologies in these areas.

Within the consumption stage, tracing energy supply directly to various consumption sectors does not identify the potential technology where energy efficiency improvements can be made. On the other hand, tracing of energy flow through various end use devices, products and services and identifying losses can provide valuable information as to where energy efficiency improvement efforts can be focused.. However, as mentioned earlier, there is currently no alignment of the methodologies involved in representing and calculating losses within the consumption stage. Such an alignment is important in improving energy efficiency, if energy flow representation is being considered for national level analysis.

Energy conservation on the other hand, is mainly related to energy demand reduction. Therefore Sankey features that trace energy demand to various consumption sectors are important in targeting energy areas for conservation programs. At the consumption stage, tracing the scale of energy flow through end use devices, products and services is useful in identifying technical devices that have high consumption; making energy labeling efforts more effective. However none of the key features identified is considered to be crucial in meeting this objective due to the challenges faced in changing practices and habits.

Table 1. Mapping of key features in Sankey diagrams with possible national-level objectives

Key features	Public awareness	Security of supply	Increasing the use of alternative energies	Identifying areas for energy savings	
				Energy efficiency improvements	Energy conservation
General Features					
1. Colour coded and labelled energy flows	✓✓	✓✓	✓✓	✓✓	✓✓
Features based on national boundaries					
1. Differentiation of energy resources and their associated carriers	✓	✓✓	✓✓✓	✓	
2. Representation of import and export flows of energy resources and carriers		✓✓✓	✓		✓
3. Representation of stock exchange and storage flows		✓✓	✓✓		
4. Representation of important energy intensive sectors (at the transformation stage)		✓✓✓	✓	✓✓	

5. Tracing of energy supply to various consumption sectors (represents energy intensive sectors separately)	✓✓✓	✓✓✓	✓	✓✓	✓✓
6. Identifies energy losses in energy transformation, transport and distribution separately				✓✓✓	
7. Boundary of energy system focused on consumption of energy without differentiating imports and exports	✓✓		✓	✓	✓✓
Features based on refining representation to trace energy use in various conversion devices, products and services					
1. Tracing alternative energy resources to various energy carriers (including conversion losses)	✓	✓✓	✓✓✓	✓✓	
2. Boundary of energy system focused on the industrial sector	✓	✓	✓✓	✓✓✓	✓✓
3. Boundary of energy system focused on the transport/building sector	✓✓	✓	✓✓	✓✓✓	✓✓

4. Energy Balance versus Exergy Balance

Sankey diagrams are most often used to trace energy flows based on energy balance/conservation concepts and the First law of Thermodynamics. Under these principles, energy input and outputs at each stage of the energy system is balanced by considering the energy content of various sources and flows. Often, differences between magnitude energy input and output are represented as losses only at relatively low levels of details and granularity (e.g. power generation losses, oil refining losses, distribution losses) which does not contribute much to energy performance objectives (shown in Table 1).

One method of effectively meeting energy performance objectives is to provide a higher level of granularity within sub-systems by representing energy losses in conversion devices, products and services. However, as previously discussed, determining and representing energy losses, especially within the consumption stage is not trivial. This is mainly attributed to the fact that using the concept of energy balance does not indicate the different usefulness (e.g. ability to do work) and quality associated with different forms of energy.

These shortcomings can be overcome by determining and analyzing exergy flows to complement the analysis of energy flows. Unlike energy, exergy is not conserved, and therefore its “destruction” provides an excellent quantifiable indication of where and how losses occur, and how improvements can be made to improve energy efficiency.

Under the second law of thermodynamics (SLT), the maximum work produced from energy flows can be determined. Exergy is defined as the maximum work that can be done by a system and a specified reference environment. Based on SLT, an exergy balance equation can be written as follows [17]:

(Exergy in) = (Exergy output in product) + (Exergy emitted with waste) + (Exergy destruction)

Some studies have made use of exergy flows in Sankey diagrams at a global level. Various forms of exergy flows associated with different energy forms such as chemical, thermal and kinetic exergy was traced through various natural and man-made conversion processes, displaying the extent of exergy destruction that takes place [18]. Similarly, using exergy balances, various sources of exergy were traced through conversion devices to identify the theoretical limits of such devices making energy efficiency policy work more meaningful [19].

Key results presented by Cullen and Allwood describe ten various loss mechanisms based on current technologies. Of which internal heat exchanges occurring from combustion mechanisms and heat transfer mechanisms exhibit the highest levels of exergy destruction [19]. This provides the motivations to improve energy flow representations through various heat exchange mechanisms at a facility level.

The study suggested allows energy and exergy flow diagrams to be overlaid with each other to identify areas where potential energy savings can be identified. At a facility level, various internal processes can be refined into stages representing the flow from left to right. By defining a boundary around these stages, energy and exergy balances can be determined.

4.1 Enthalpy and entropy reference states and physical exergy

This study only considers physical exergy; the maximum amount of work that can be obtained from a system before it reaches thermal and mechanical equilibrium with the specified reference state.

Physical exergy, Ex_{ph} calculations are based on (Dincer and Rosen Chapter 2 Pg 27) and resented in Eq. (1), where H is the enthalpy and S is the entropy of a flow with respect to a reference state defined by P_0 and T_0 (pressure and temperature respectively)

$$Ex_{ph} = (H - H_0) \; -T_0(S - S_0) \tag{1}$$

The reference state for calculating physical exergy is also known as the dead state. The absolute values of enthalpy and entropy at a single state point do not have much physical significance. The significance arises when the differences in enthalpy and entropy of two different state points are considered. Therefore an arbitrary value can be defined for the enthalpy and entropy of various flows.

4.2 Identifying potential energy performance improvements in a regasification facility

A typical regasification facility is used to illustrate how potential savings can be identified by overlaying energy and exergy flows together. The regasification facility discussed only involves open rack vaporisers (ORVs). ORVs regasify liquefied natural gas (LNG) from temperatures below -160 ^{o}C to room temperature through a heat exchange process with sea water at room temperature and pressure. With today’s insulation technologies minimal heat is lost to the surroundings, also in such a process heat losses may in fact speed up the process of regasification, making heat exchanger systems in ORVs highly energy efficient.

The regasification facility can be refined into two stages; pumping mechanism and ORV that includes a heat exchanger. Based on standard enthalpy values of water and methane, the energy that flows through a regasification facility is presented in Fig. 2. Electricity delivered to the system is calculated based on Bernoulli’s equations. It demonstrates a very small degree of energy losses that stem from the pumping mechanism.

An exergy analysis of this process provides a completely different picture (Fig. 3). It represents almost similar amounts of exergy destroyed in the pumping mechanisms, but almost all of the exergy being destroyed in the heat exchanger. The exergy input of electricity is assumed to be the same as the energy input. The Sankey representation of energy and exergy flows here presents a large potential for energy savings that could be realised in the regasification process. Minimising the temperature difference through cascading heat would result in potential savings and a reduction in exergy destruction of LNG.

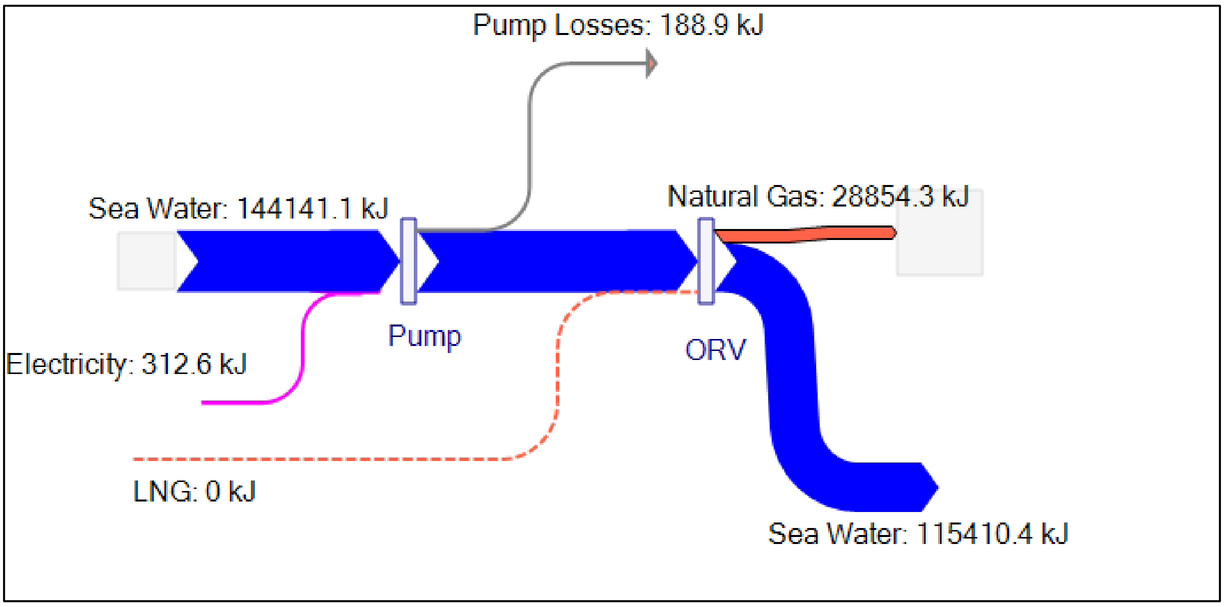

Figure 2. Sankey diagram of energy flows in an ORV

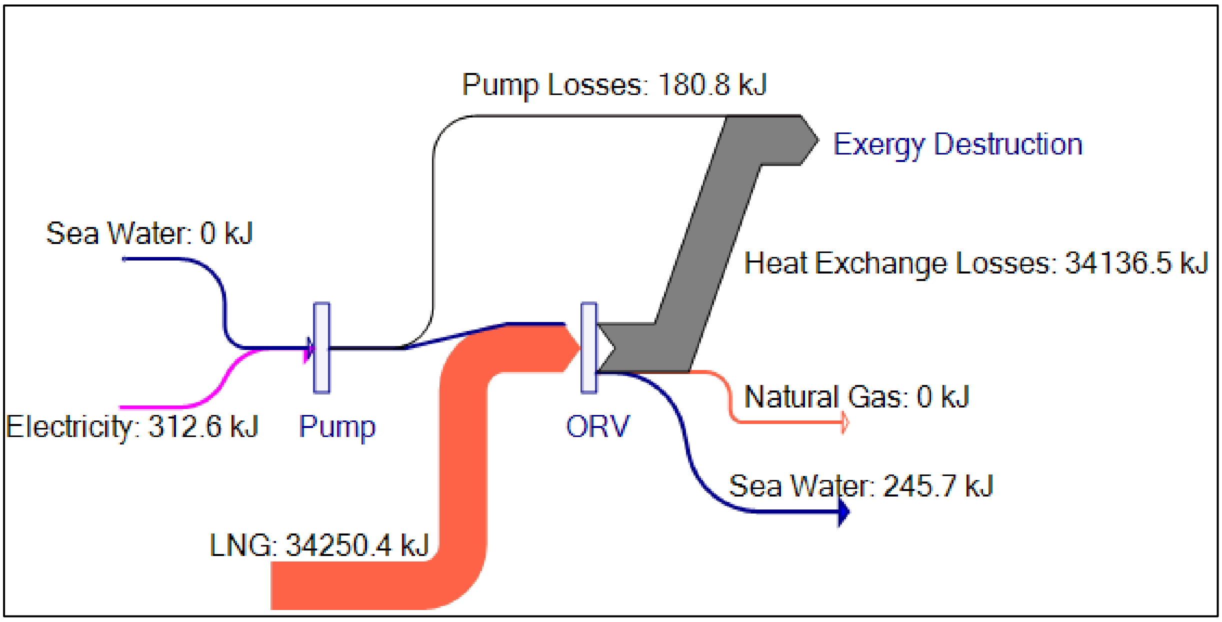

Figure 3. Sankey diagram of exergy flows in an ORV

5. Future Research on Sankey Diagram Framework

One key area that is identified for future research is how improvements can be made to collect and analyze data as part of refining the energy sub-systems to trace energy in conversion devices, end use products and services in Sankey diagrams. This area remains a challenge in the industrial sector where various companies may pose restrictions on the extent of information they wish to divulge to government agencies. Also restrictions may be imposed on how much information collected can be publicly available for research purposes.

Another area is to research further into the use of *exergy* flows in Sankey diagrams for fulfilling energy performance improvement objectives at a national level.

As the world continues to grapple with climate change challenges, research on carbon flows in relation to energy and exergy flows can also be considered. The inclusion of carbon flows produced at various stages of the energy system may provide a visual representation of the embodied carbon in various end us products and services; allowing environmental objectives of energy planning to be evaluated.

With the increasing use of alternative and renewable energy in our future energy mix, energy storage becomes increasingly important to maintain grid integrity and reliability. With higher levels of data collection and smart meter technologies integrated within our system, energy flow representation over shorter periods; weekly, daily or even hourly may provide additional insights into how alternative resources could be effectively utilized over different time periods.

Finally, the "economic value" representation of energy flows also requires significant research effort. All Sankey diagrams currently reviewed are not very useful for economic analysis due to the absence in assigning economic values to various energy flows. Economic value representation has particular significant in industrial ecology, since value usually overrides quantity when decisions on energy and material flow are to be made today. A prominent example of such value representation was provided by the Nobel Prize winner Wassily Leontief in 1985 [20].

6. Conclusion

The matching of various key features with different objectives provides a framework for designing Sankey diagrams for national level and facility level analysis. The analysis makes three unique contributions to our understanding of how Sankey diagrams are to be designed for various objectives.

- Energy loss representation at low levels of granularity do not contribute significantly to energy performance objectives;
- Features based on refining sub-systems to trace energy use in various conversion devices, products and services provides additional insights to energy performance objectives;
- Overlaying energy and exergy Sankey diagrams provides a possible alignment of how energy losses are calculated and represented, identifying potential areas for energy performance improvements.

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