Energy 36 (2011) 6172–6183

Contents lists available at ScienceDirect

Energy

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

Energy harvesting, reuse and upgrade to reduce primary energy usage in the USA

Alexander S. Rattner, Srinivas Garimella*

G.W. Woodruff School of Mechanical Engineering, Georgia Institute of Technology, 801 Ferst Drive, Atlanta, GA 30332, USA

ARTICLE INFO

Article history:
Received 7 June 2011
Received in revised form
26 July 2011
Accepted 27 July 2011
Available online 3 September 2011

Keywords:
Waste heat
Energy quality
USA energy resources
Thermal
Geocoded
Pulp and paper

ABSTRACT

Two-thirds of input energy for electricity generation in the USA is lost as heat during conversion processes. Additionally, 12.5% of primary fuel and 20.3% of electricity are employed for space heating, water heating, and refrigeration where low-grade heat could suffice. The potential for harnessing waste heat from power generation and thermal processes to perform such tasks is assessed. By matching power plant outlet streams with applications at corresponding temperature ranges, sufficient waste heat is identified to satisfy all USA space and water heating needs. Sufficient high temperature exhaust from power plants is identified to satisfy 27% of residential air conditioning with thermally activated refrigeration, or all industrial refrigeration and process heating from 100 to 150 °C. Engine coolant and exhaust is sufficient to satisfy all air conditioning and 68% of electrical demands in vehicles. Overall, this study demonstrates the potential to reduce USA primary energy demand by 12% and CO_2 emissions by 13% through waste heat recovery. A detailed analysis of thermal energy demand in pulp and paper manufacturing is conducted to demonstrate the methodology for improving the fidelity of this approach. These results can inform infrastructure and development to capture heat that would be lost today, substantially reducing USA energy intensity.

1. Introduction

Energy demand in the United States is satisfied by a range of primary fuels harvested for their stored chemical energy, secondary fuels produced as a byproduct of manufacturing processes, and non-chemical energy from wind, hydraulic, solar, nuclear, and geothermal sources. Historical trends in USA primary energy usage are compiled in Fig. 1 from data reported by the USA Energy Information agency (EIA) [1–6]. Here, delivered electrical energy from solar, wind, and hydraulic sources is reported instead of primary energy input, and the energy density of nuclear fuel (U_3O_8) is estimated to be 517 GJ kg^{-1}. Even with rapidly increasing wind and solar energy consumption, thermal energy from chemical and nuclear sources still accounts for 97% of USA primary energy. Additionally, inspection of Fig. 1 reveals that USA primary energy demand is increasing by up to 3% per year.

As shown in Table 1, 43.9% of the energy for USA consumption is converted to electricity. Calculations based on data from the EIA Electric Power Annual Handbook [7] show that 93.4% of this energy is converted to electricity through thermal processes that release significant "waste heat" via exhaust streams, condensers, gas coolers, and other heat transfer components. Many manufacturing processes and vehicle combustion engines also release substantial quantities of waste heat at useful temperatures. However, 10.8% of energy from primary fuels with high combustion temperatures (>1500 °C) and 12.5% of generated electricity are used for low-grade tasks, including space heating, water heating, and process heating below 100 °C. Thus, there is great potential to reduce demand for high-grade energy by applying waste streams from high-temperature processes to these needs. Recent developments in sorption technology [8] enable the replacement of electrical input for air conditioning and refrigeration, which accounts for 13.0% of electricity generation and 5.7% of primary fuels [7,9–12], with waste heat. Advances in thermoelectric devices can reduce the mechanical power demand of vehicles alternators by converting engine waste heat directly to electricity [13].

Thermal cascading – the identification of appropriate uses for energy at each temperature range – is an ancient concept. In Paleolithic times, fires were harnessed for lighting (high quality energy), medium temperature cooking, and low-temperature space heating. Modern developments include combined-cycle, co-generation, and tri-generation power plants and recuperative heating in manufacturing processes. Recent increases and fluctuations in the cost of energy combined with growing concern about global warming have increased interest in waste heat utilization as a national policy for improving energy security and reducing

* Corresponding author. Tel.: +1 404 894 7479; fax: +1 404 894 8496.
E-mail address: sgarimella@gatech.edu (S. Garimella).

0360-5442/$ – see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.energy.2011.07.047

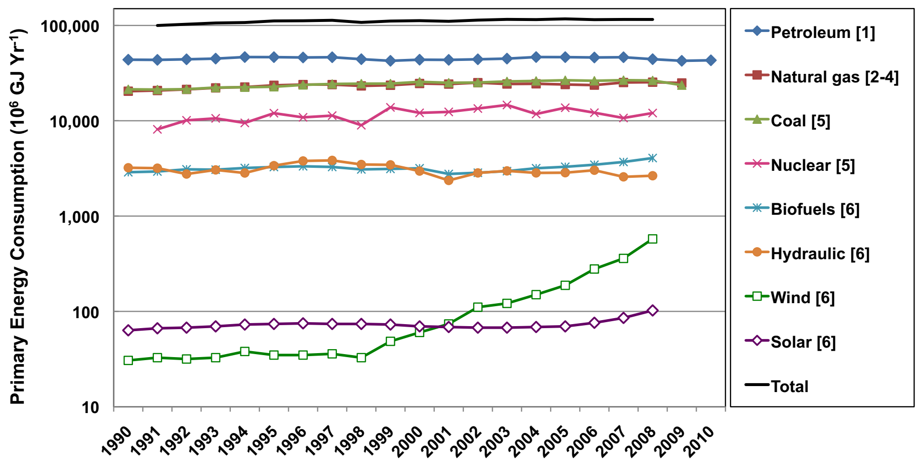

Fig. 1. Trends in USA primary energy consumption.

environmental impact [14–16]. However, published data about waste heat availability and applications are often limited or unavailable.

The USA Energy Information Agency is the predominant source for information about energy use in the United States for power generation [7] and industrial [9], commercial [10], and residential [11] applications. EIA studies track energy use by fuel source, geography, and economics, but do not publish thermodynamic information such as the corresponding temperatures and efficiencies. Usage mechanisms are not always available; for example, electric resistance space heating is grouped with electric heat pumps. Transportation energy usage data are published by the USA Department of Energy through Oak Ridge National Laboratory [12]. Fuel economy and vehicle types are reported, but fuel efficiency, waste heat fractions, and temperatures are not tracked. Some industry specific waste heat data and process temperatures are available from the International Energy Agency [17]. The major portion of published information about energy efficiency and waste heat sources and applications is available only in dispersed form throughout numerous academic and industry publications.

The objective of this study is to compile and estimate (when necessary) quantities and temperatures of waste heat sources and applications for the United States. Collected and calculated data are consolidated into a database, which can answer sophisticated questions about USA waste heat with structured query language (SQL) queries. While providing a comprehensive understanding of waste heat distribution and utilization possibilities across the country, the fidelity of this database can further be progressively improved by conducting detailed studies to replace representative temperatures and energy demands with more accurate values collected from topical literature. This refinement process is demonstrated for the pulp- and paper-manufacturing sector as a guide to future efforts. The database is employed here to demonstrate the potential to satisfy a large fraction of USA energy demand with waste heat.

Table 1
Primary energy usage in the United States by sector (10^6 GJ yr^{-1}).

Energy source	Power plants [7]	Industrial [9]	Commercial [10]	Residential [11]	Transportation [12]
Petroleum	770	135	159	1558	27,450
Natural gas	7637	11,926	2166	5038	697
Coal	24,298	1354	–	–	–
Nuclear	8260	–	–	–	–
Secondary fuels	1060	2833	–	–	1068
Biofuels	355	666	–	–	602
Hydraulic	866	–	–	–	–
Wind	124	–	–	–	–
Solar	7	–	–	–	–
Total	43,514	16,914	2325	6595	29,816
% of USA total	43.9	17.1	2.3	6.7	30.1
Estimated waste heat	24,236	613	–	–	18,118

2. Methodologies and calculations

2.1. Waste heat availability from power plants

Annual surveys conducted by the EIA [7] provide information about USA electricity generating power plants down to the individual generator level, most recently in 2007. However, the published generator thermodynamic data only include nameplate capacity, fuel source, and power cycle (internal combustion, steam turbine, etc., but without additional details about cycle configuration). Estimates of efficiency and outlet stream temperatures and energy fractions must be developed to calculate available waste heat from power plants.

The EIA electric power survey publishes annual power generation by fuel type. Ratios of generated power to installed capacity are calculated for each fuel. Individual generator productivities are estimated as the corresponding fraction of capacity for the primary fuel source. Efficiency, waste heat fractions, and waste heat temperatures vary significantly between generators, even between those with similar fuels and energy cycles. Still, estimates are developed by compiling data from published power plant thermodynamic analyses and data sheets for representative generators (Table 2). It should be noted that in EIA reports, efficiencies and waste heat fractions are reported separately for the gas and steam generators in combined-cycle power plants. This convention has been adopted in the present work also. Thus, the relatively low individual generator efficiencies (35.3%, 20.1% [18]) combine to yield a more familiar overall efficiency (55.4%) consistent with modern plants. Coolant outlet temperatures for stationary internal combustion generators are rarely reported, but are assumed equal to those found in vehicles (85 °C) [19,20]. The compiled information may be biased toward higher efficiencies since data come from plants that have been studied for thermodynamic improvements and manufacturer data for modern hardware. Thus, the waste heat fractions presented here may be conservatively low.