# Energy Systems Analysis

**Investigators**
A.J. Simon, GCEP Energy Systems Analyst; Rebecca Hunt, GCEP Software Engineer; Clare Swan, GCEP Information Technology Administrator; Weston Hermann, GCEP Assessment Analyst; Jodie Prud'homme, Adam Simpson, Graduate Researchers, Stanford University

## Introduction

The goal of Energy Systems Analysis is to develop a methodology for measuring the impact of technologies from an energy- and materials-usage standpoint. The Energy Systems Analysis team supports the goals of GCEP building a technical portfolio and assessing the impact of research by developing software models that allow quantitative comparisons of energy technologies. As part of the GCEP Central Assessment effort, the activities of the analysis team allows GCEP to better understand where opportunities exist to reduce the emissions or increase the efficiency of energy systems and devices.

This year, the focus of the analysis group has shifted its emphasis towards supporting the GCEP Portfolio selection process and energy network analysis. Although the methodology has become more "top-down" than it has been in the past, the underlying principles of the work remain the same.

The Analysis group builds models of mass and energy flow through existing and proposed energy technologies. The technologies under study encompass the same range of subjects that GCEP is investigating: harvest, storage, distribution, conversion and use of energy. The models are designed to encompass varying levels of technical detail. Each model tracks the inputs and outputs as well as intermediate states for the material and energy streams used by a device. Such models can pinpoint the most efficient and least efficient steps of device operation, and provide the researcher with an in-depth understanding of the technological challenges faced by engineers and scientists. This work will help GCEP locate promising research opportunities for low-emissions, high-efficiency energy technologies and identify barriers to the large-scale application of these new technologies.

## Background

The term "Energy Systems Analysis" at GCEP is used to describe modeling efforts aimed at:

1. quantifying the performance of individual devices and
2. characterizing the interactions between various devices.

The tools, process, and results from the Systems Analysis work towards these goals is described in the next section.

Analysis of energy systems is taking place at numerous organizations across the globe. In these groups, energy systems analysis work may focus on different goals than those of GCEP. These goals may include:

- tracking the fate of resources as they are processed through the energy economy;
- determining the economic feasibility of various energy use scenarios;
- predicting the economic outcomes of energy policies;
- finding the causes of, and solutions to, technological, market or policy failure.

The GCEP Assessment team focuses on the first option in the list above, tracking the fate of resources as they are processed through the energy economy. Other “Energy Analysis” systems are being developed at numerous organizations elsewhere: public and private; governmental, corporate and academic. For a more detailed list of these systems, please see the 2005 GCEP Technical Report.[1]

**Results**

The Energy Systems Analysis team has continued to refine its software toolbox and to extend the set of energy conversions it can analyze. This year, a major effort in energy flowchart mapping has been initiated. This effort requires new tools.

*Software Tools*

The Analysis Team has taken advantage of commercially available and open source software to facilitate the development of thermodynamic system models. Each software package has been selected based on its ease of use and development, its ability to provide the technical components required, and its reasonable cost. There is not a single tool that provides all of the features required for successful energy system analysis, therefore several packages are required. The following list describes the main tools used by the Analysis Team and how they are being adapted for thermodynamic analysis.

1. Matlab (from The Mathworks) has been chosen as the programming language of choice for the Systems Analysis Group[2]. Matlab is an extremely flexible programming environment with a wide array of computational tools readily available for adaptation to energy system simulation. All of the models and tools described in the next section are written in MATLAB.

2. Python has been investigated as a secondary programming language. Python shares many of the advantages of Matlab in that it is a modern scripting language which facilitates quick program development in a flexible development environment. Python is free and entirely open-source, and has many extensions available which replicate the more advanced mathematical and graphical features of Matlab. An interface for Cantera (below) is available for Python.

3. Cantera (Open Source) is a chemical kinetics and thermodynamics data package that is being developed at Caltech and is released under an open source license.[3] The Analysis Group is using Cantera for chemical equilibrium calculations and kinetics information. The Systems Analysis Team has worked with the developer of the Cantera code base to expand the Pure Component chemical calculations by writing a Carbon Dioxide module and submitting a Heptane module. Additionally, the team has worked to enhance the functionality of the MATLAB interface.

4. The Aspen Suite (from AspenTech) is an integrated modeling environment which tracks mass and energy flows and has a wide range of property data not available in other

tools.[4] The Analysis team accesses the property packages in Matlab via an ActiveX interface.

5. MySQL (Open Source) is a database management system that is recognized as a leader among free, scalable and extensible data repositories.[5] As a natively relational database, it is well-suited to the task of tracking the connections between energy resources, carriers and transformations.

*Modeling Tools*

In order to build the energy models in a productive and streamlined manner, the GCEP Energy Systems Analysis team has developed a number of software tools. These tools provide a number of functions. First, they provide a consistent interface to programmatically access the different packages described above. This reduces the learning curve and allows more efficient development. Second, a framework has been developed that allows the interchange of information between these packages and between system models, allowing developers to work with multiple underlying tools within one model in a clear, consistent, and realistic manner.

One tool, titled "State Toolbox for Cantera" provides an object oriented interface to Cantera chemical state properties. Written in MATLAB, the State Toolbox was written specifically to enable the tracking of multiple thermodynamic states. Additionally, this package fixes some of the shortcomings of the Cantera property and equilibrium calculations and extends the property calculations. The State Toolbox also adds the ability to calculate the exergy of given states. Using this toolbox, Energy Systems students in the mechanical engineering department were able to perform the exergy analysis shown in Figure 1 (next page) in the space of about one week.

The State Toolbox for Cantera is available to the open source coding community.[6] By making this code available to the wider community, the Analysis team hopes to foster development of and with the model. Providing a shared framework is one step toward integrating our models with those at other institutions.

Another component of the tool framework is GCEP Streams. The GCEP Streams package not only provides a representation of physical systems, but also assists the energy systems modeler in integrating multiple models and tools used in their work. GCEP Streams are used in device level modeling to represent different streams of matter or energy. This software package can integrate tools developed with the State Toolbox, Aspen, and Cantera, allowing the programmer to access the chemical calculations or property packages while building a higher-level model.

This year, a model of electromagnetic radiation as a stream of energy was added to the GCEP streams toolbox. Eventually, that functionality will enable the analysis of solar photovoltaic and solar thermal technologies.

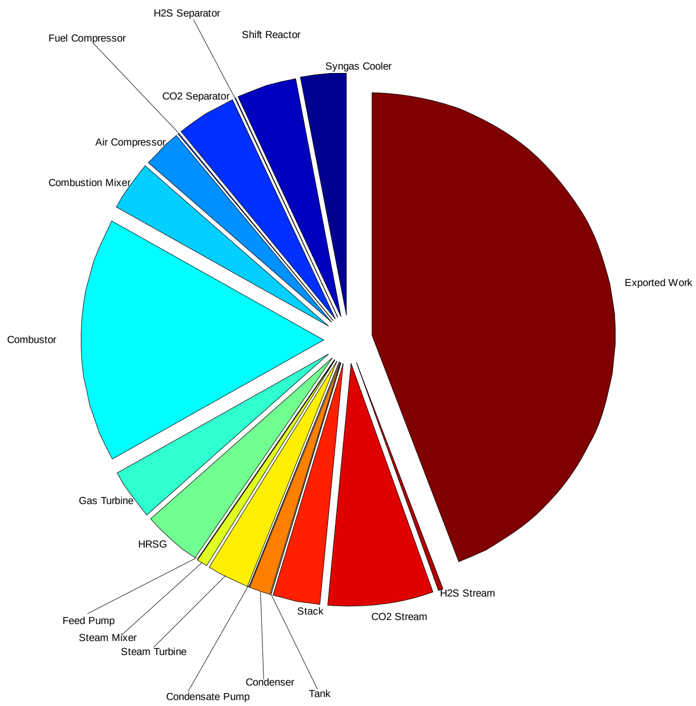


**Figure 1**: Exergy analysis of an IGCC plant with $CO_2$ separation. The largest fraction of fuel exergy is exported as work, while the largest exergy destruction takes place in the gas turbine's combustor.

*Exergy and Carbon Maps*

A mapping of human-managed exergy flow on a global scale was completed this year. The data are extensively annotated and there resulting graphic has proved to be both useful and provocative. GCEP has received several requests for copies of the figure as well as explanations of the various flows. The figure is reprinted here in 4 parts: Figures 2a through 2d.

The charts include information about the natural fluxes of energy and carbon through the environment (generally driven by the >100,000 TW of sunlight reaching the earth), as well as information at the human industry scale (0.003 - 5.0 TW). This is the first time that this range of scales has been incorporated into this type of analysis.

Of immediate interest are the links between the scales on which previous analyses have been based. The generally accepted number for the scale of the global human-managed energy system is 15 TW. That number is visible as the sum of Coal, Oil, Gas, Hydro, Nuclear (heating value basis) and Biomass (as fuel). However, given the quantity of biomass that is actively managed in agriculture and forestry, humans actually manage far more exergy, although not for traditional energy services.

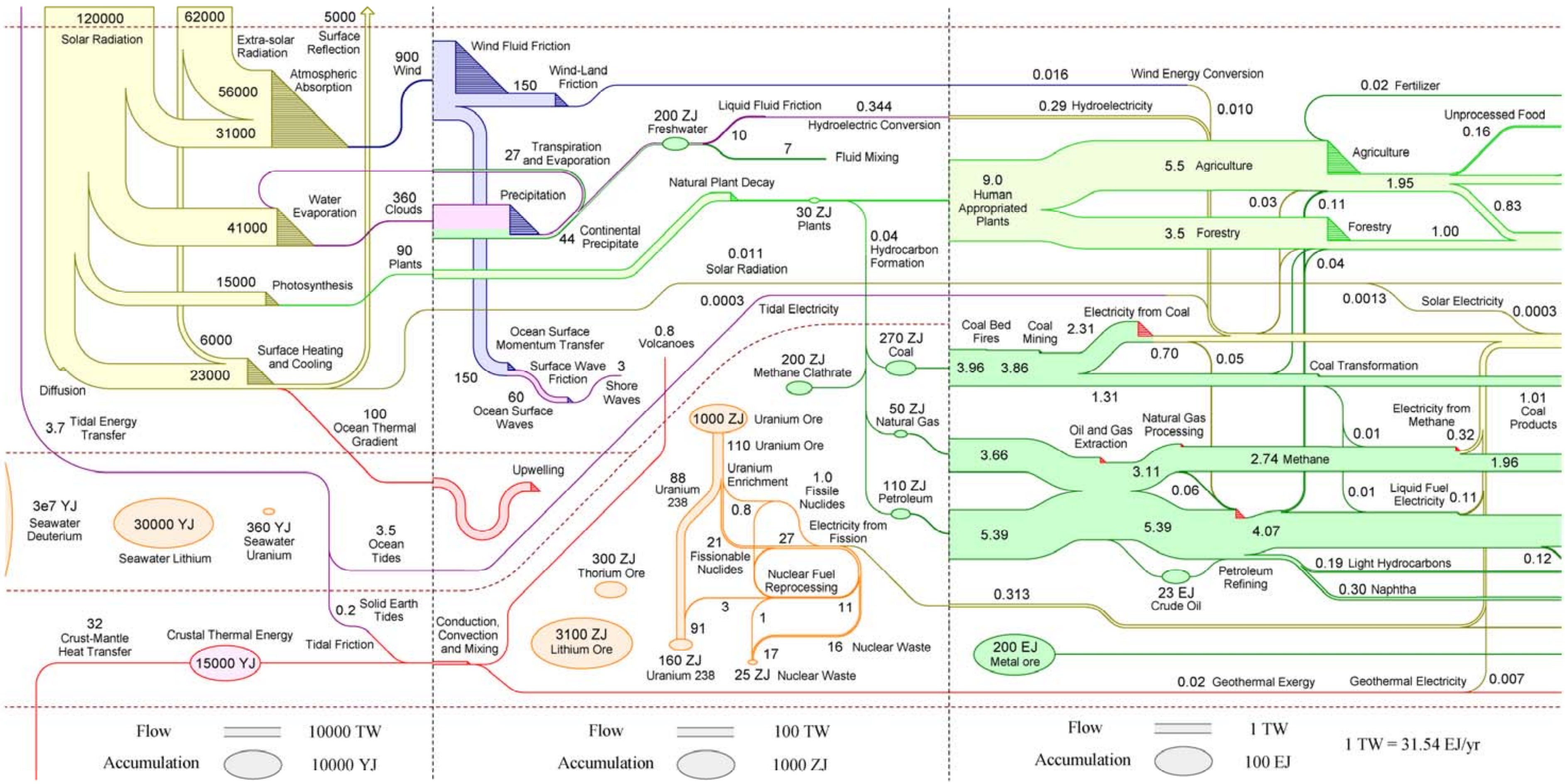


**Figure 2a** : Global exergy flow, accumulation and destruction (continued in Figure 2b). Brown dotted lines represent the boundaries of the system of interest: that under anthropogenic influence between the stratosphere-mesosphere and crust-mantle interfaces. Black dotted lines designate scale changes (see legend at bottom, this page). Exergy flow is generally from left to right. Color codes are provided in the continuation of this figure on the next page.

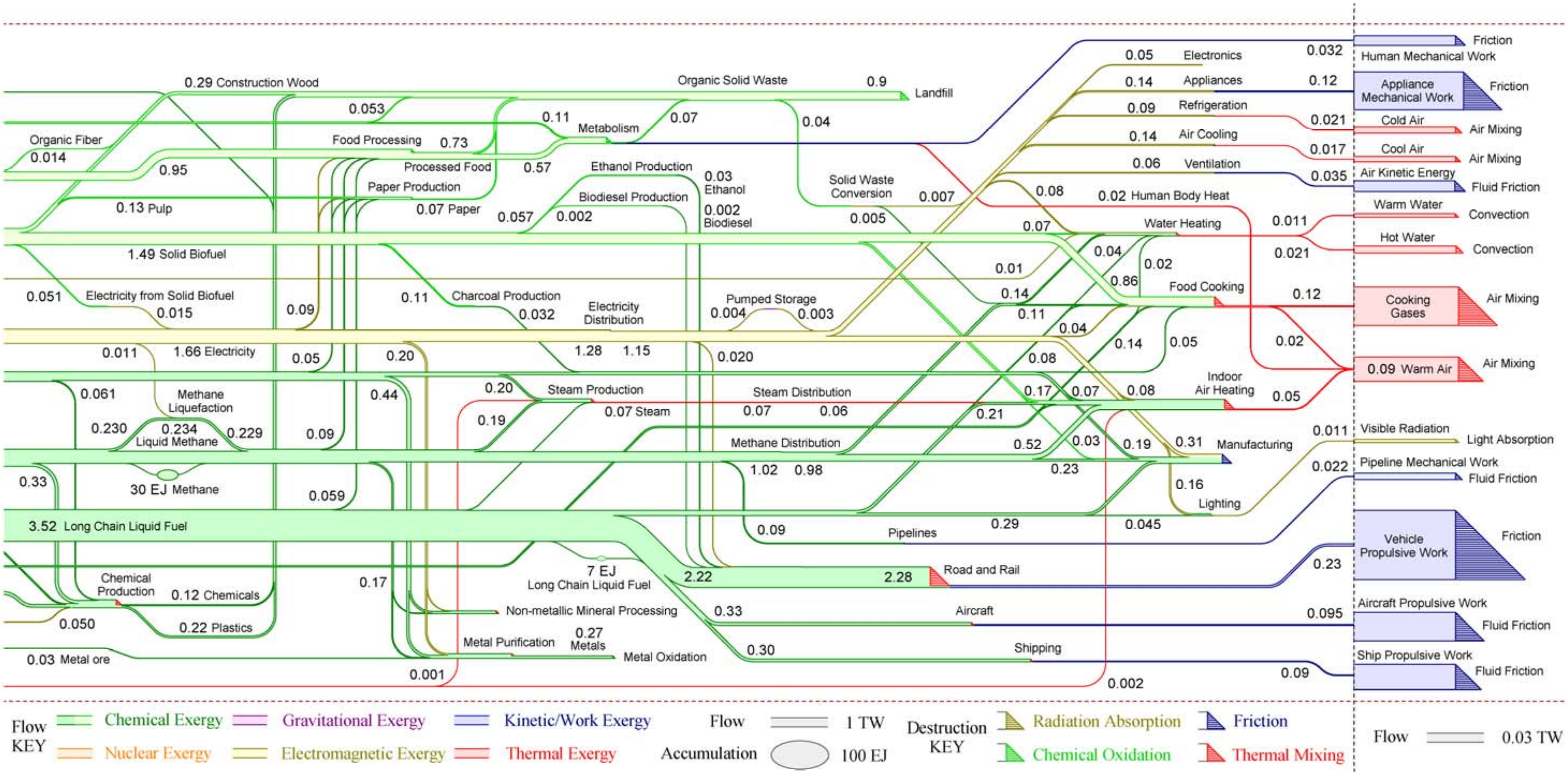


**Figure 2b** : Global exergy flow, accumulation and destruction (continued from Figure 2a). Brown dotted lines represent the boundaries of the system of interest: that under anthropogenic influence between the stratosphere-mesosphere and crust-mantle interfaces. Black dotted lines designate scale changes (see legend at bottom, this page). Exergy flow is generally from left to right.

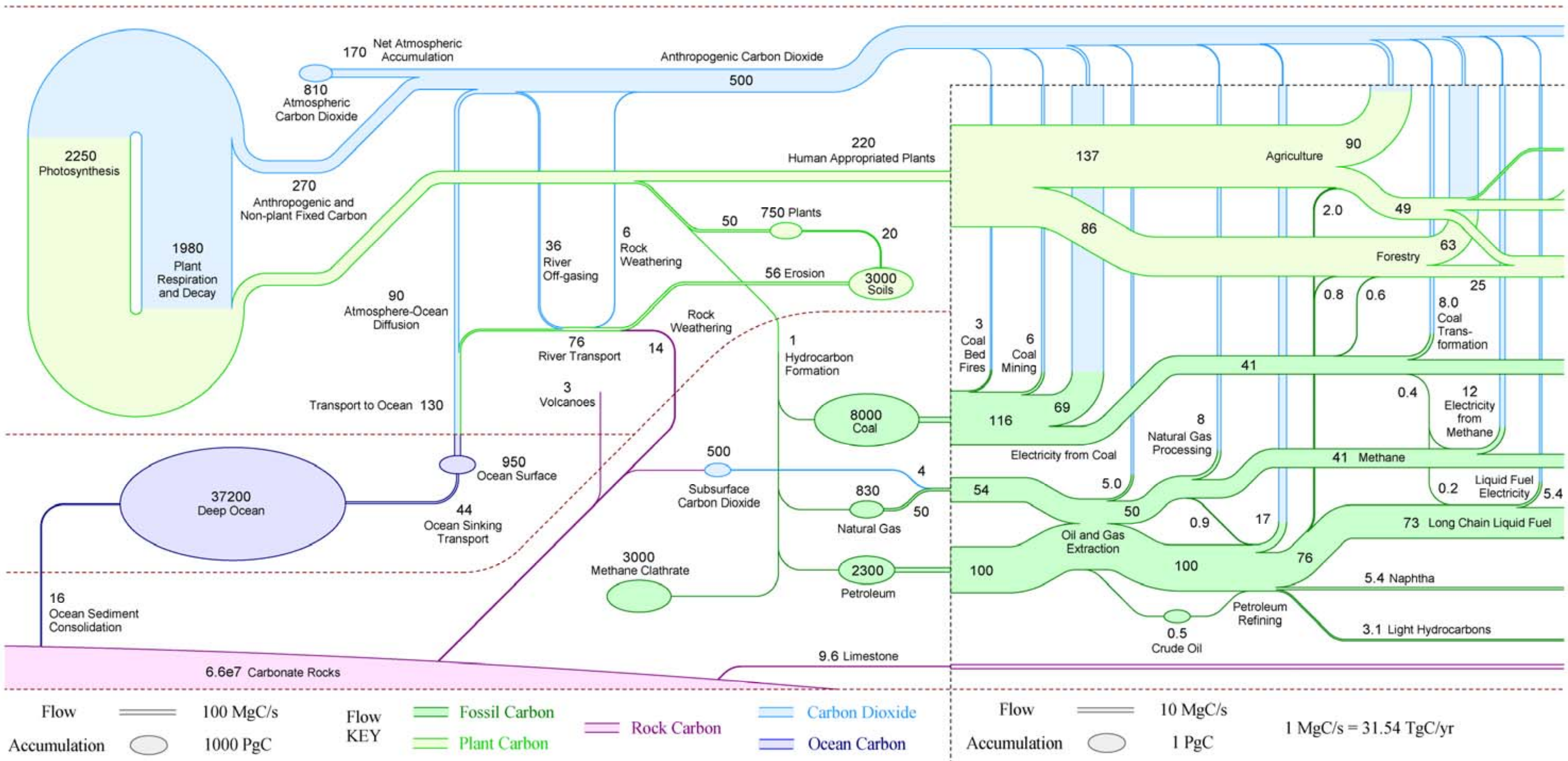


**Figure 2c** : Global carbon flow and accumulation (continued on Figure 2d). Brown dotted lines represent the boundaries of the system of interest: that under anthropogenic influence between the stratosphere-mesosphere and crust-mantle interfaces. Black dotted lines designate scale changes (see legend at bottom, this page). Carbon flow is generally counter-clockwise. A key to the color codes is provided in the continuation of this figure on the next page.

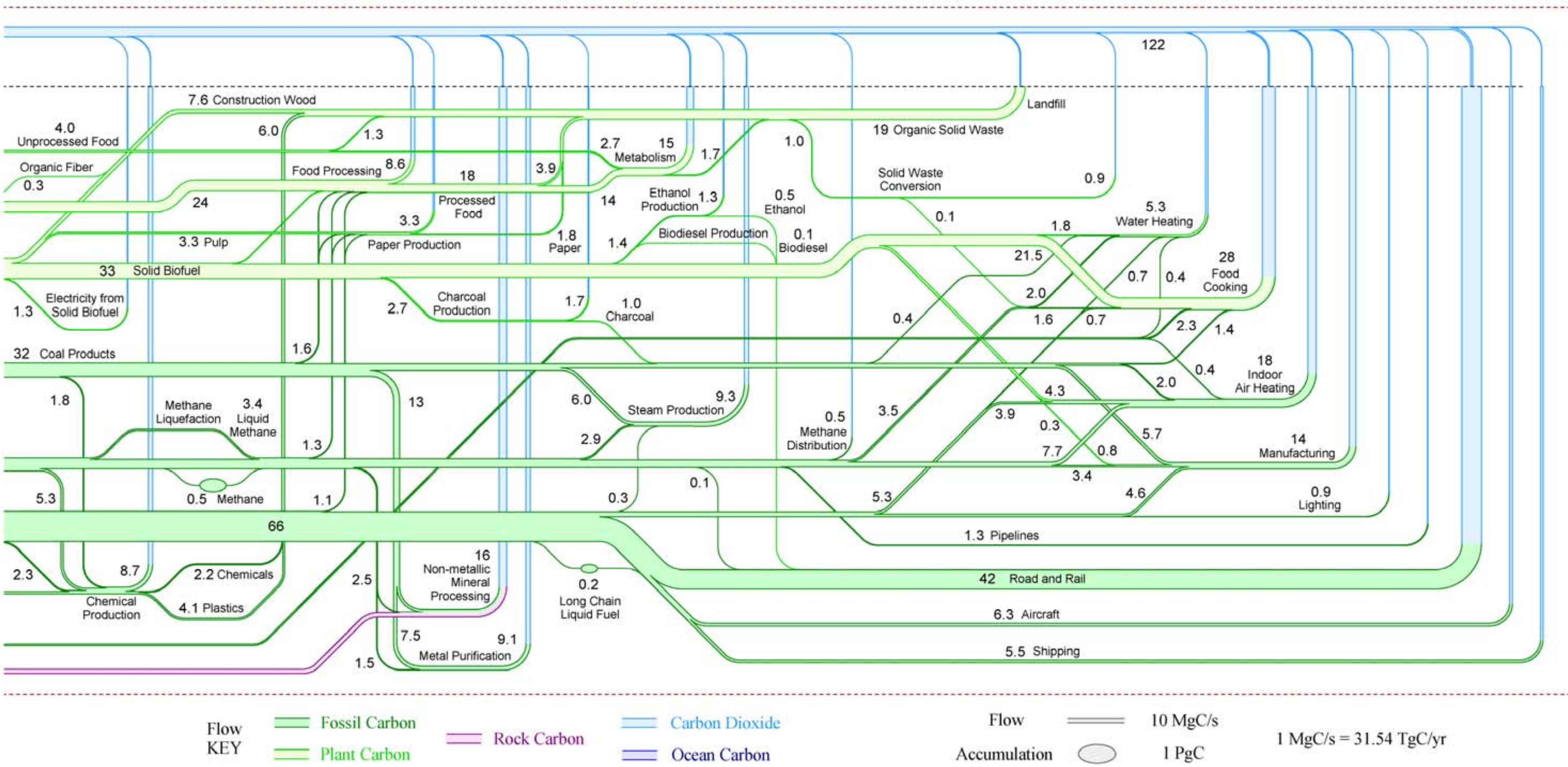


**Figure 2d** : Global carbon flow and accumulation (continued from Figure 2c). Brown dotted lines represent the boundaries of the system of interest: that under anthropogenic influence between the stratosphere-mesosphere and crust-mantle interfaces. Black dotted lines designate scale changes (see legend at bottom, this page). Carbon flow is generally counter-clockwise.

In contrast to the 15 TW of energy that is managed, the sum of energy services that are provided as work is approximately 1.5 TW. This indicates that our energy system has an overall 2nd law efficiency of about 10%. This is a weighted-composite efficiency that includes the poor exergy efficiency of services such as space-heating (4%) and the relatively high efficiency of air travel (28%). At 10% overall efficiency, there are abundant opportunities for technology to contribute to reducing carbon emissions while maintaining the same level of energy services humanity enjoys today.

This analysis also tallies about 9 GT carbon/yr of anthropogenic emissions. Again, this sum is a composite of the major industrial $CO_2$ sources with caveats regarding the biological carbon managed in agriculture and forestry. The standard emissions sources are easily identified (Coal-Fired Electricity, Transportation, Heating and Cooking), and the major industrial sources are also apparent (Refining, Cement, Metals).

There are more than 50 different energy and material carriers and more than 100 different transformations in the above figures. While it would be possible to describe each transfer and transformation of energy and carbon in detail, the complexity of the interconnections limits the impact of a narrative description of the flow charts. The visual appeal of the data is embodied in the ability to "trace through" a carrier or transformation of interest and "branch out" to other parts of the energy system. The systems analysis group is now in the process of entering the data into a mySQL database which will serve as the backbone web-based software which will allow users to graphically search the figure, references and explanations.

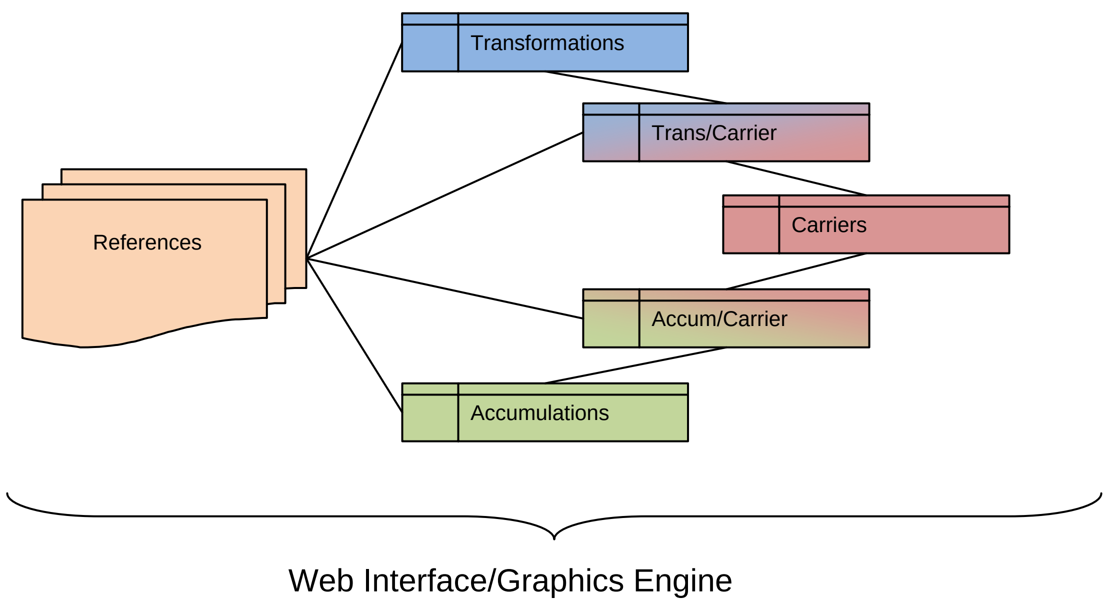


**Figure 3**: The database is structured so that a query language can process real interconnections between energy carriers, transformations and resources. In this representation, the complex structure of the reference table has been collapsed for readability.

The structure of the database is intended to reflect the reality of the energy system. Energy conversion systems (control volumes) are represented by database entries in the "Transformations" table. Transfers of energy or matter into or out of those control volumes are represented by entries in the Transformation-Carrier table. The Transformation-Carrier table defines the relationship between an energy conversion, its feedstocks and its products.

Beyond the data representing physical transfers and transformations of energy, there is also information about where the data came from (references) and that explains the significance of the data (notes). Because all of this data is stored in mySQL, it will be relatively straightforward to publish it on the web.

**Future Plans**

The Energy Analysis Team will continue to support GCEP's mission of identifying opportunities for research and breakthrough technologies by providing informative tools, models and analysis of energy technologies. In the coming year, we will publish the web version of the exergy and carbon flow charts. We will also extend our ability to evaluate thermodynamic working fluids to a more fundamental view than that offered by Cantera, or Aspen.

**References:**


[1] "2005 GCEP Technical Report" available online at http://gcep.stanford.edu/research/technical_report/2005.html

[2] MALTAB produced by Mathworks http://www.mathworks.com

[3] Cantera, hosted by the California Institute of Technology http://www.cantera.org

[4] Aspen, produced by AspenTech http://www.aspentech.com

[5] MySQL, produced by MySQL AB http://www.mysql.com

[6] State Toolbox for Cantera package available at http://project.sourceforge.org/sct-cantera


**Contacts**


A.J. Simon: ajsimon@stanford.edu