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ENERGY LIFE-CYCLE ANALYSIS MODELING AND DECISION SUPPORT TOOL

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For 26 years, Battelle Memorial Institute has operated Pacific Northwest Laboratory (PNL) for the U.S. Department of Energy (DOE). As one of DOE's five multi-program national laboratories, PNL develops and deploys technology for national missions in energy and the environment. The Energy Information Systems Group, within the Laboratory's Computer Sciences Department, focuses on the development of the computational and data communications infrastructure and automated tools for the Transmission and Distribution energy sector and for advanced process engineering applications.

1.0 ENERGY SYSTEM - DECISION DRIVERS

Policy and Politics, Economics, Environmental Issues, Social Momentum, and Technology are the primary decision drivers affecting the energy industry. These decision drivers are felt at all levels of the energy life-cycle. For example, the emphasis within the Transmission and Distribution energy sector to maximize the use of the existing infrastructure, minimize impacts to and from the environment, and to enhance energy efficiency and conservation are the direct result of economic and environmental pressures. The direction our energy future takes will be determined by these drivers and their constraints. ***The constraints presented by these drivers represent research and development opportunities.***

Policy and Politics

Policy is the single most important driving factor in the development of science and technology. Policy statements and directions influence the economics of addressing technological issues. To date no energy policy with a vision has been implemented by any of the industrialized or energy producing nations. Energy developments are taking place based on marketplace demand and momentum. Unless a leading nation or political organization (such as the United Nations) devises such a visionary policy and backs it up with actions, the development of energy related technologies will continue to be constrained by marketplace economics.

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Most energy policies have traditionally focused on an economic stress avoidance philosophy as opposed to one of leadership, or one which establishes end-use goals and drives toward them. Non-energy related policies and regulations such as those directed at environmental issues also push the energy industry. For example, in the United States the Clean Air Act and Resource Conservation and Recovery Act (RCRA) are forcing the energy industry to modify their operating practices. Summarily, the energy industry is in a reactive rather than proactive mode.

Economic Factors

The principal economic factors affecting the energy industry (from the science and technology viewpoint) include: cost of raw materials; costs associated with environmental impact, mitigation, and restoration; and technology development and commercialization costs. Ultimately the system cost must be broken down into $/kw or BTU. Currently most economic models appear to be one-dimensional in their approach--they consider only direct economic cost. That is, they start by accumulating the costs of the feed stock and end by determining the price of the output product. New models need to be developed which look at the energy life-cycle. For example, what are the real costs of extracting, cleaning, and burning coal not only in terms of dollars, but also in terms of environmental costs? How do by-products generated within the energy production processes affect the total life-cycle costs? How can environmental impact costs be measured? How can "avoided costs" be incorporated into an economic assessment model, and what are the costs of waste management? ***Thus one research area is the development of models which can help determine points along the fuel/energy generation process which can be improved upon to make an alternative fuel cost-competitive.***

Environmental Issues

Numerous environmental and related constraint factors impact energy process costs throughout its life-cycle. Among the more common environmental issues are site characterization, raw material extraction, regulations, restoration, and environmental impact costs. These issues focus on impacts to the environment, there are also environmental impact on the energy infrastructure.

Momentum

Related to the lack of strategic energy policies is a complacent attitude by the general populace. There is no general or even discipline-specific consensus as to an energy policy approach. With oil subsidies in place, there are few incentives for the current power holders to form a new energy policy constituency. There will be little government or major

industrial enthusiasm to pour resources into major new energy alternatives until such time as a major crisis, such as occurred during the early seventies, or the comfort level of the general populace of the richest nations is severely impinged upon.

The current low cost of oil and the energy produced therefrom may, however, actually have a silver lining in that it is forcing the alternative energy industry to improve their technologies over and beyond what would be acceptable if oil were at a much higher price.

Technology

The production of "energy" is perhaps one of the most multi-disciplined industries in existence. Each phase or process within the energy life-cycle requires cross-domain expertise. For example, fluid-mechanics, chemical engineering, mechanical engineering and computer science disciplines all need to come together to address coal-slurry pipelines, or solar energy capture, storage and conversion, or for hydrogen fuel-cell design and operation.

Several issues are hindering the development of new energy related technologies:

- there is no strategic energy policy to provide a focus

- the playing field for developing new energy alternatives is not even; what policy does exist generally provides subsidies to favorite fuels or technologies such as the petroleum industry;

- there is a long delay period between concept, invention, prototyping, and operational installation - even then it may or may not be cost competitive

- development of new facilities and operational infrastructure incur high capitalization costs and usually encounter difficulties in obtaining permits and insurance.

Note that most of these issues have more to do with policy and economics than with technology issues. ***The technology issues are more often encountered when trying to drive an existing process to new levels of efficiency and cost competitiveness. A mix of technologies which, when used together, will provide maximum advantage to the energy process(es) and are more important than a single "best" technology.***

2.0 SCIENCE AND TECHNOLOGY MEGATRENDS

The industry drivers described above are fueling three basic trends/technology advances in the energy industry. The first two trends, energy efficiency and environmental impacts, appear to enjoy a level of global awareness. The last trend, conservation, is focused largely in the U.S. and Japan.

Efficiency

Energy efficiency targets the loss of energy from transmission and distribution through the point of end use. Construction of energy efficient buildings, lighter weight cars, and higher performance (greater efficiency) appliances such as furnaces, stoves and refrigerators are receiving considerable attention. Less attention is being given to the heat conversion, and power generation aspects of the energy cycle.

Environment

There appear to be conflicting trends within the environmental arena. From a global perspective, the preservation of the earth's environmental resources is receiving more attention than ever before. Locally, however, it would appear that there is strong resistance to addressing environmental considerations in favor of immediate economic gratification. At best we appear to be attempting to achieve some balance between environmental impacts and economic progress. Unfortunately, all of our economic models run from an economic progress standpoint, not from an environmental cost perspective. ***How does one equate environmental loss or degradation to a monetary unit so we can actually begin to compare the same units of measurement?***

Conservation

Conservation addresses energy usage from a behavioral standpoint. Given that the world's human population will most probably continue to expand and that expansion will continue to require resources, how can we modify the cultural infrastructure such that the amount of resources used per person is minimized. Efficiency and conservation work very closely together. Efficiency addresses energy usage from the equipment standpoint and conservation addresses it from a social aspect.

3.0 ENERGY SYSTEMS PERSPECTIVE

Today's approach to the energy industry is fragmented. Each sector of the energy life-cycle is analyzed, regulated, and managed as a discrete industry. A life-cycle approach to the industry treats it from a systems-oriented perspective. The energy life-cycle is viewed as a set of inter-linked generic energy processing tasks:

1. extraction and collection
2. storage, transmission, and distribution
3. conversion
4. end use

which are successively applied to the energy as it is transformed from its initial primary source to its final end use, and in the case of closed cycle systems, recycled back to the source.

Extraction and collection are comprised of those tasks involved in making the energy source available to the system. Storage and distribution refer to activities required to match the spatial and temporal characteristics of the supply to those of the demand, and may involve stockpiling, transportation, transmission or co-location. Conversion involves those steps, occurring at any stage between extraction and end use, in which energy is converted from one form to another, in order to exploit the natural advantages of a particular form of energy. These processes include using the fuel to create heat or steam, conversion of that heat or steam to work or electricity, conversion of mechanical energy (kinetic or potential) to work or electricity, direct conversion of the fuel to electricity, or converting one energy source or fuel into another fuel.

Finally, end uses constitute the demand for energy (especially electricity). To provide maximum flexibility, ***we can view the energy demand as a demand for services: lighting to a certain illumination level, heating or cooling to a certain comfort level, transportation in a preferred manner, production of industrial products that serve a particular purpose. By viewing demand in this way, we can meet that demand by substituting fuels, energy conversion processes, and lighting, heating, transportation, and production methods. By meeting end use demand more efficiently, we use less fuel, produce fewer emissions, and require less generation capacity without diminishing quality of life.***

4.0 ENERGY LIFE-CYCLE ANALYSIS MODEL (ELCAM)

PNL has proposed the development of an Energy Life-Cycle Analysis Model (ELCAM). The objective of ELCAM is to develop a detailed conceptual model of an integrated energy life-cycle model which can be used to examine alternative energy system options, evaluate the total costs associated with each option, identify technology bottlenecks, and suggest research directions to alleviate them.

The systems perspective of the energy life-cycle can be represented graphically. As Figure 1 shows, energy can be supplied from any of a number of sources using one or more conversion steps. Electricity, for example, can be produced from any of the sources through any of the paths shown. Two of the ways electricity can be produced from coal are: using conventional combustion to produce steam followed by a steam turbine (Figure 2), and coal gasification followed by combustion in a gas turbine (Figure 3), respectively.

The end user's needs may be met equivalently using different paths also. For example, rather than heating a home with electricity, a user can burn natural gas or use solar heating. For personal transportation, one can drive an automobile powered by a gasoline-fueled

internal combustion engine (Figure 4) or (among other options) a fuel cell-powered electric car for which the hydrogen for the fuel cell was generated by solar power (Figure 5). Different options can be evaluated to find the best way to meet end user needs.

An integrated energy life-cycle model can be used as a decision support system to identify targets of opportunity for research and technology development. These targets of opportunity would reflect the energy life-cycle process bottlenecks, which, if solved, could radically improve the efficiency, conservation and sustainable future of the system. Analysis of the energy cycle pathways enables one to identify key steps or major problems. One can then focus research efforts in those areas.

An integrated energy life-cycle model will enable different energy production and use options to be examined qualitatively and quantitatively. The effects on the entire energy system can be evaluated. Each step from source to end use has associated with it costs such as economic, environmental, energy security, etc. By weighing all costs and benefits of each step from source to end use, the optimum paths (mix of fuels and processes used) can be identified to meet society's energy needs. This optimum solution will be strongly affected by the weighting of the various costs. If environmental preservation is considered most important, the optimum energy pathways are vastly different than it would be if the goal were strictly to minimize economic cost.

ELCAM System Capabilities

ELCAM represents a vision. It is being developed as an enabling infrastructure to numerous projects. ELCAM's initial prototype will demonstrate the conceptual ability for the user to examine existing source, energy production, and end use scenarios, construct new scenarios from a predefined set of possibilities, and to examine cost, performance, and environmental impact results for the selected scenario.

It is expected that the ELCAM prototype system will demonstrate the following capabilities:

- Modes of Operation (demonstrable for a subset of the energy cycle)
  - Path Analysis
    - Source to energy product
      - for fixed source, analyze paths to energy product (e.g., Figures 2 and 3)
      - for fixed energy product, analyze paths from sources.
    - End use
      - for fixed end use, analyze paths (e.g., Figures 4 and 5).
  - Node/Link Analysis

- Conversion (energy product/energy product)
  - for a specified conversion (e.g., heat to work), view options and their performance and applicability

- Overall Energy Life-cycle Analysis
  - Examine either predefined scenarios or scenarios saved from Path Analysis or Node/Link Analysis
  - Identify Bottlenecks/Problem Areas - nodes or links which satisfy specified criteria (e.g., link common to most paths, path producing most emissions) will be identified
  - Capabilities
    - Subsystem Path Analysis
      - scenario review (base case or one of predefined list)
      - scenario construction (select path from allowable links)
      - scenario query (retrieval/analysis and compare to base case)

        * cost (for production of electricity)
        * environmental impacts (air emissions)
        * energy consumed (per unit energy product or end use).

5.0 CONCLUSION

The energy industry is being forced to operate in new ways and under new constraints. It is in a reactive mode, reacting to policies and politics, and to economics and environmental pressures. The transmission and distribution sectors are being forced to find new ways to maximize the use of their existing infrastructure, increase energy efficiency, and minimize environmental impacts, while continuing to meet the demands of an ever increasing population.

The creation of a sustainable energy future will be a challenge for both the soft and hard sciences. It will require that we as creators of our future be bold in the way we think about our energy future and aggressive in its development. The development of tools to help bring about a sustainable future will not be simple either. The development of ELCAM, for example, represents a stretch for the computational sciences as well as for each of the domain sciences such as economics, which will have to be team members.

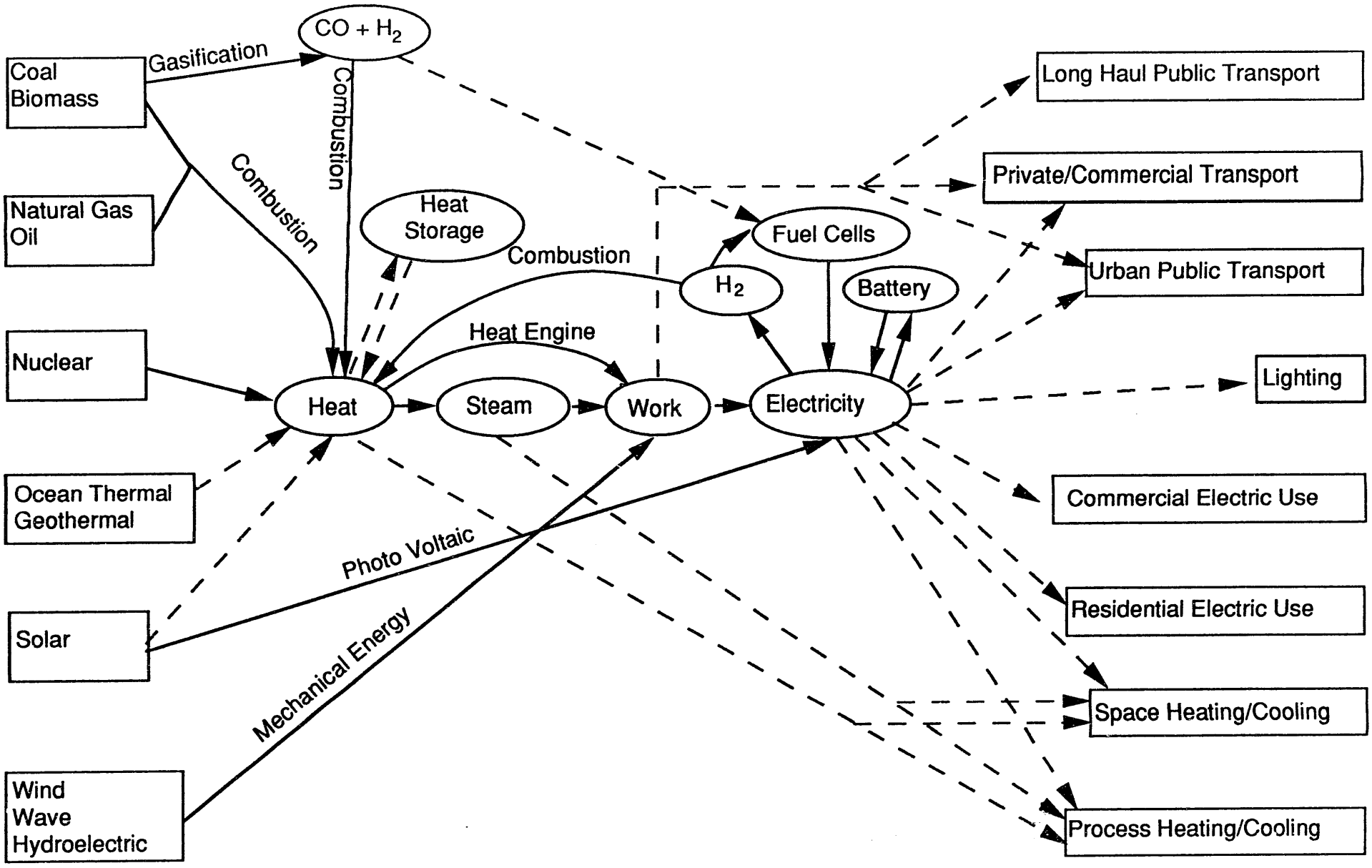

Figure 1. Energy Cycle Model
Basic Energy Paths

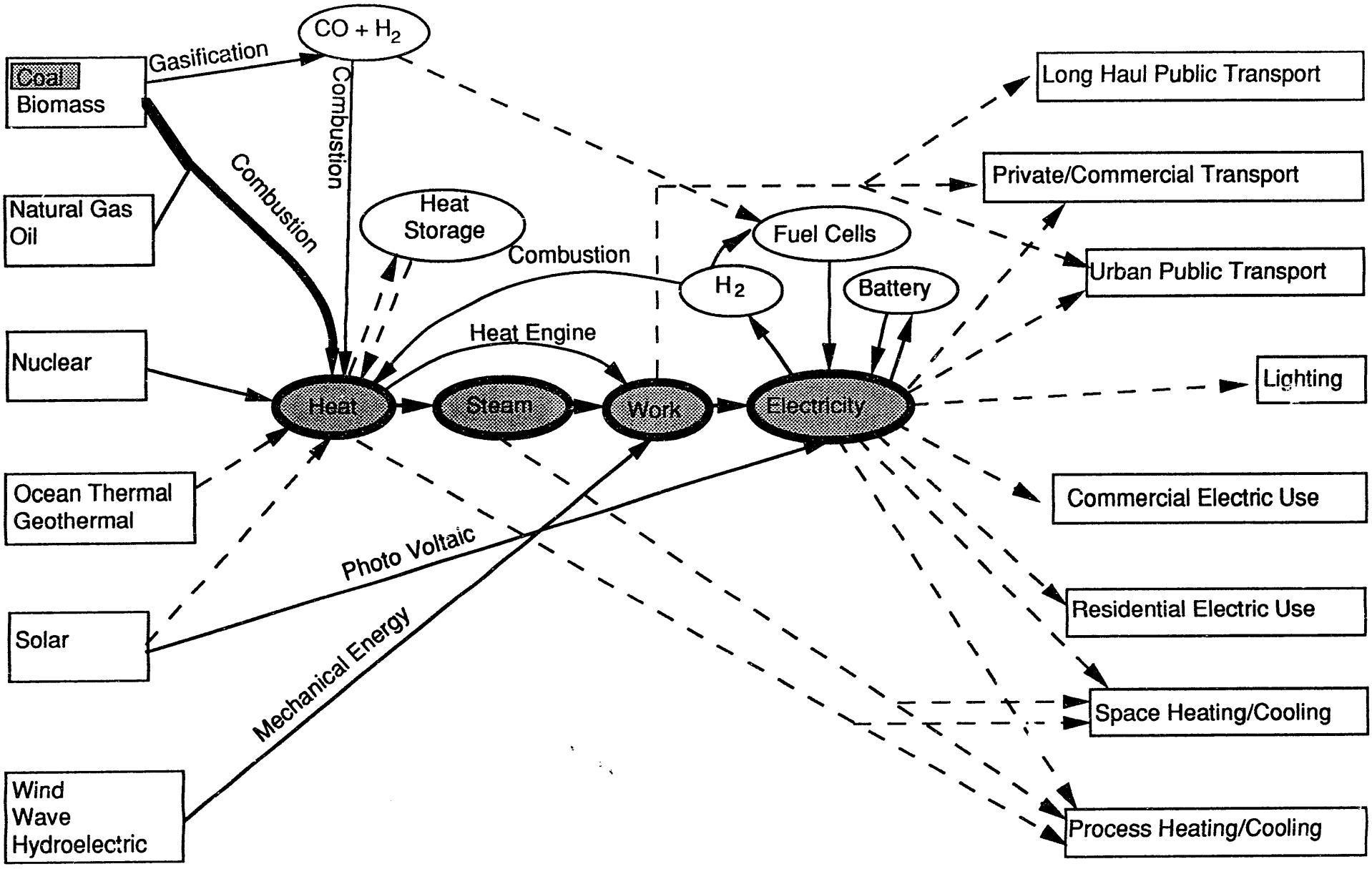

Figure 2. Energy Cycle Model
Conventional Coal-Fired Power Plant

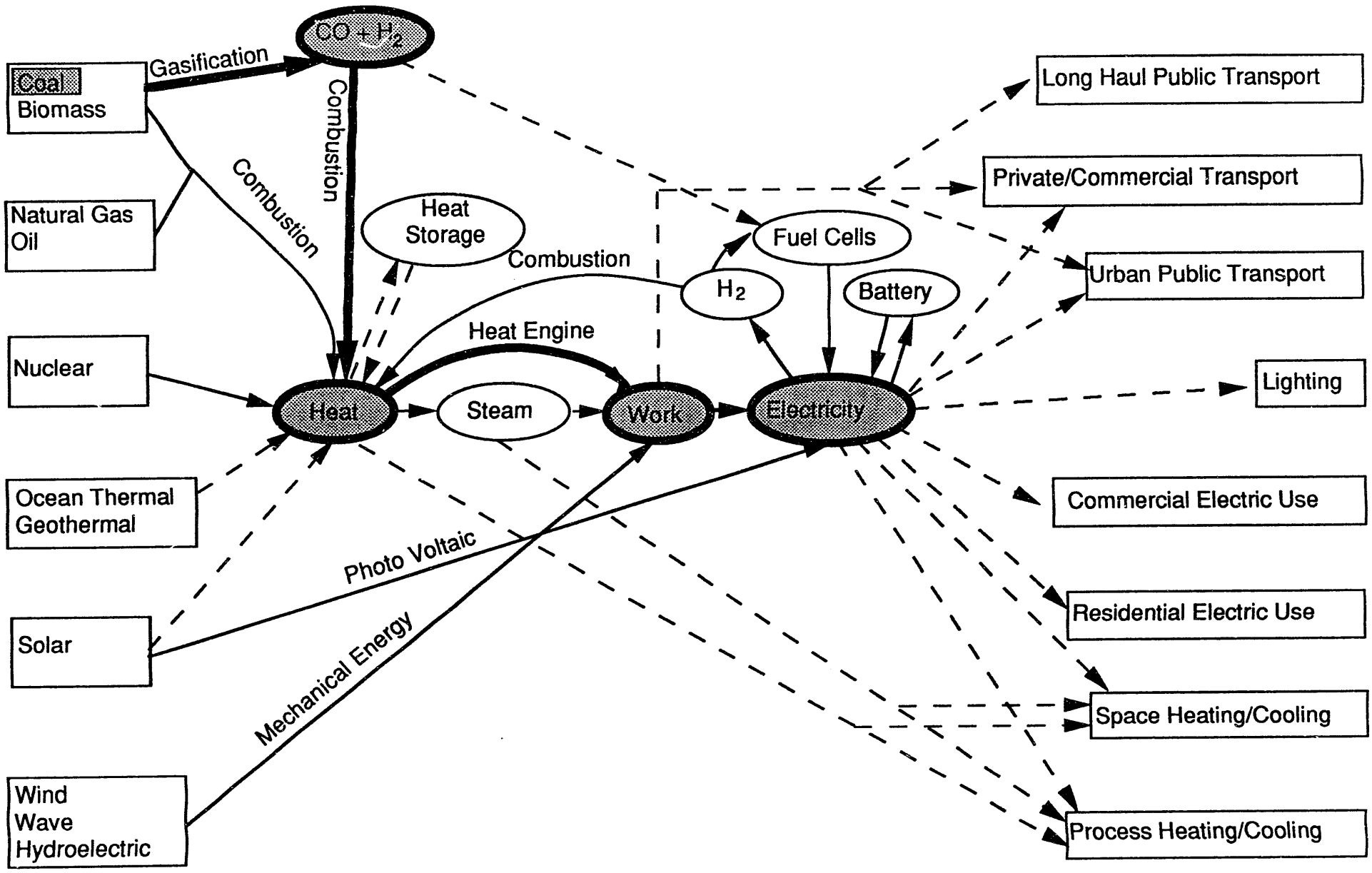

Figure 3. Energy Cycle Model
Coal Gasification, Gas Turbine

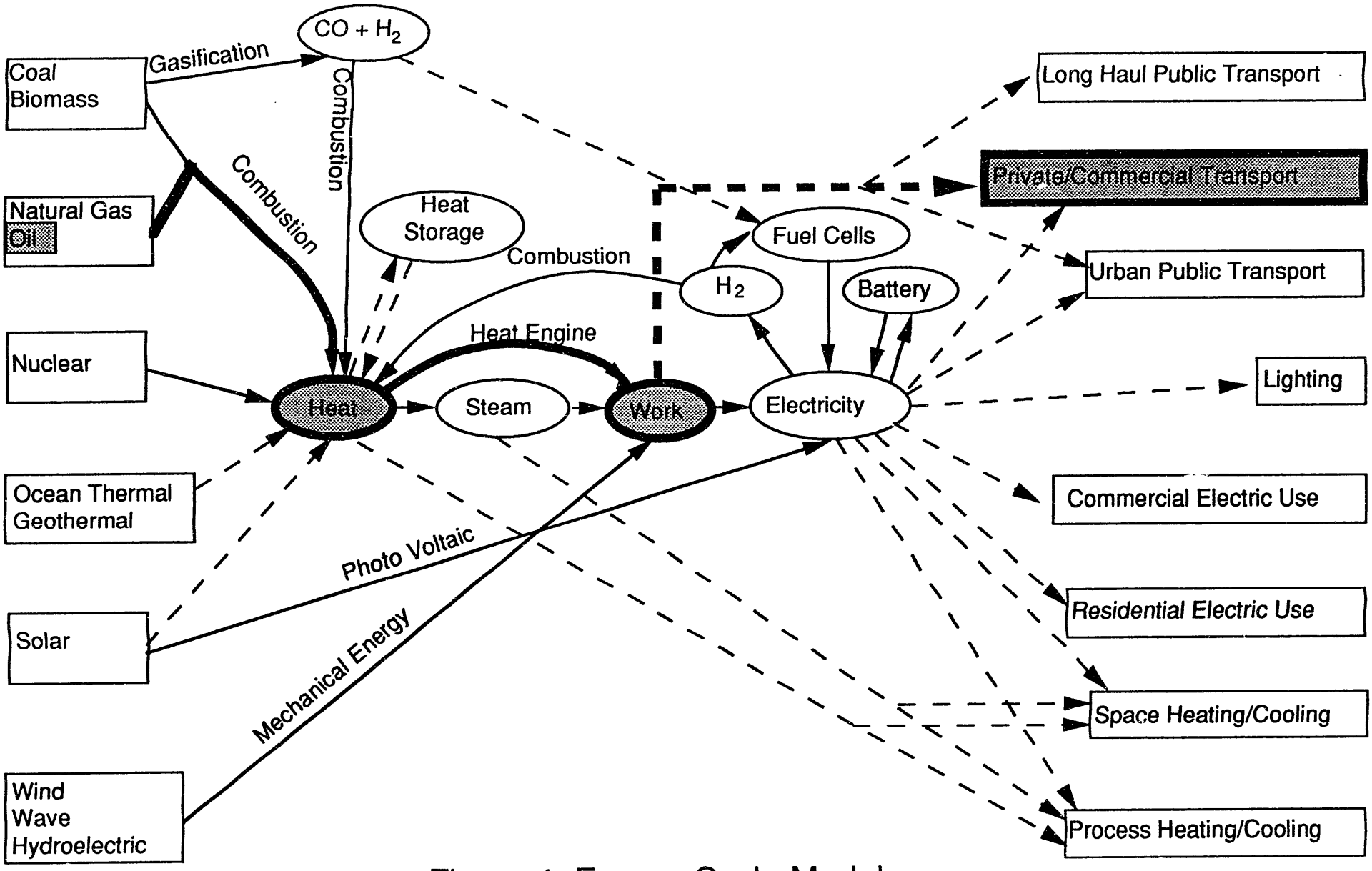

Figure 4. Energy Cycle Model
Conventional Automobile Gasoline
Fueled Internal Combustion Engine

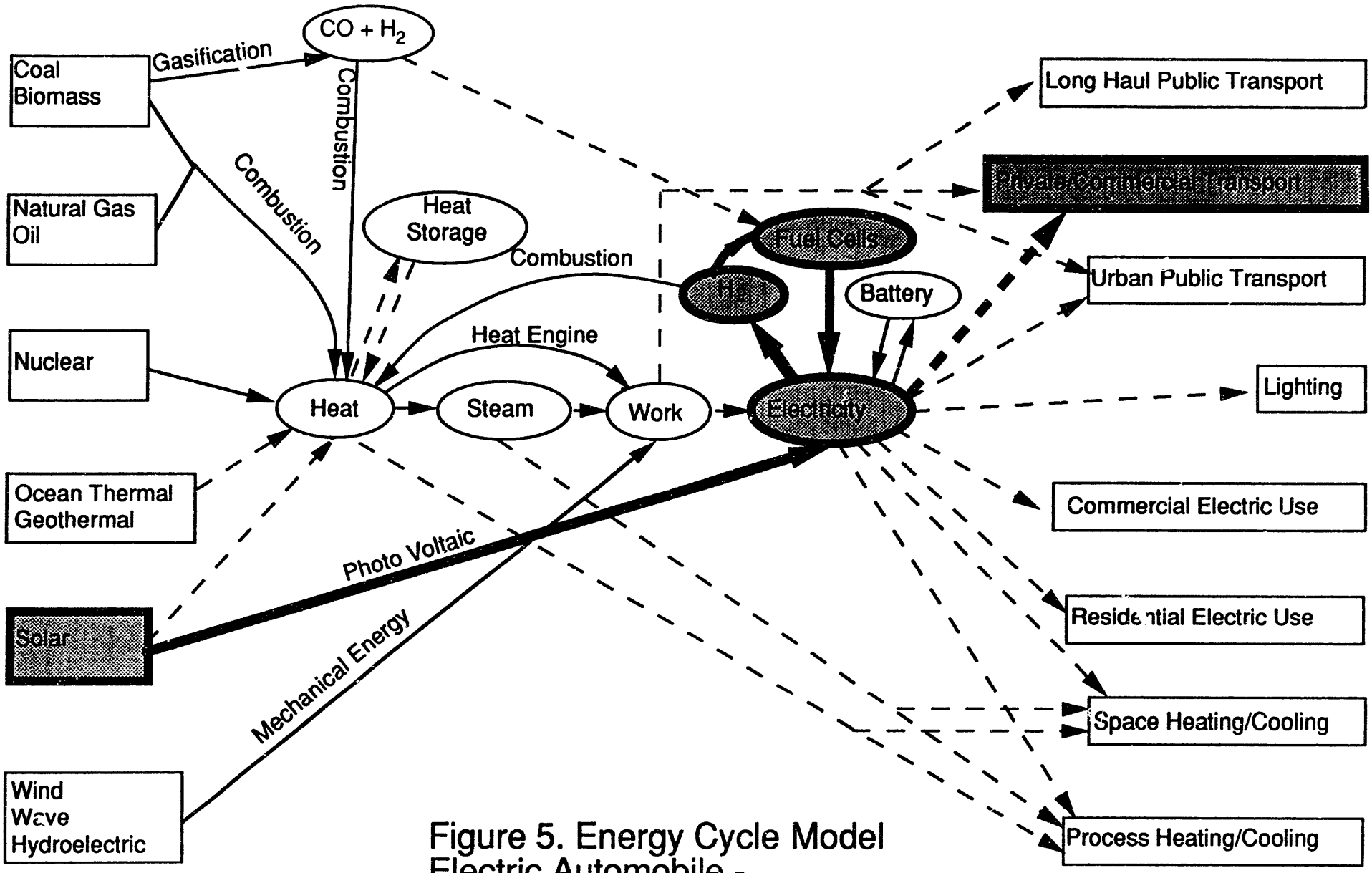

Figure 5. Energy Cycle Model
Electric Automobile -
Solar Generated Hydrogen,
Fuel Cell Generated Electricity

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